Coherent mode superposition as the source of complex radio pulsar polarization
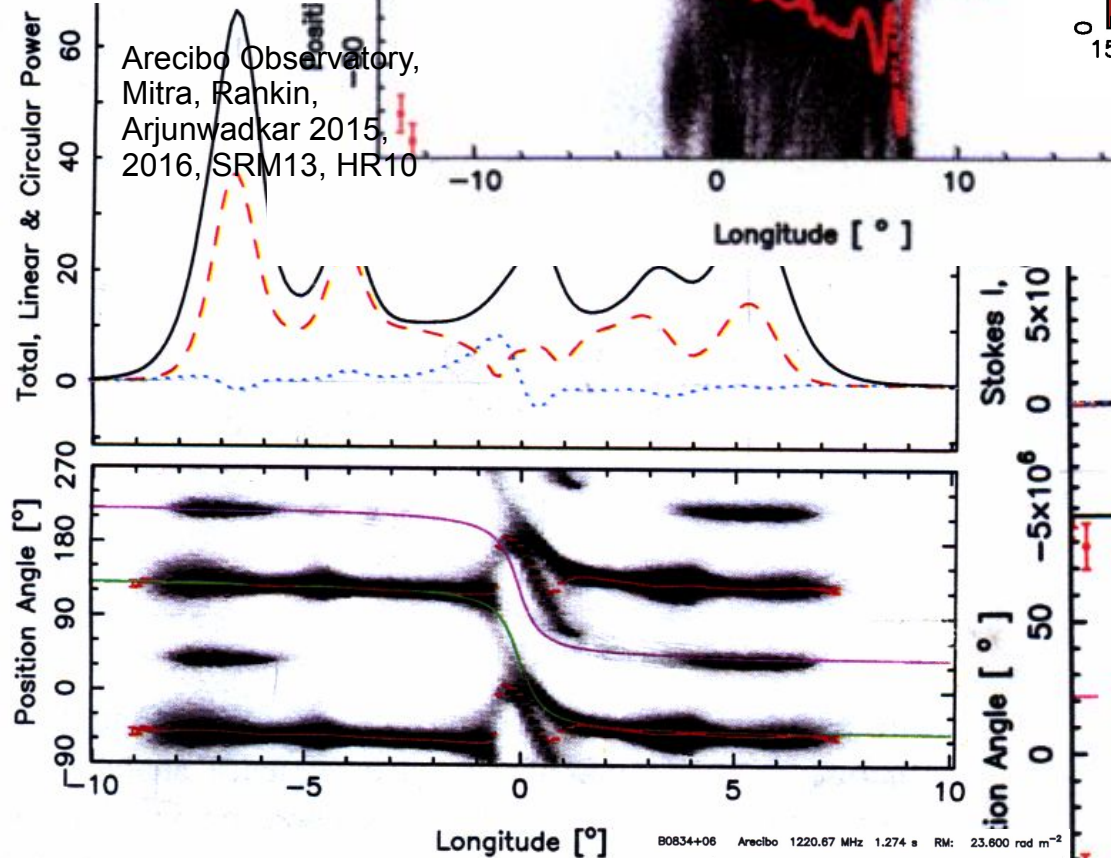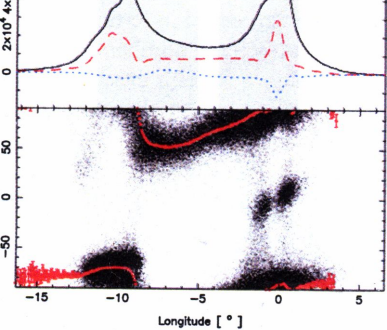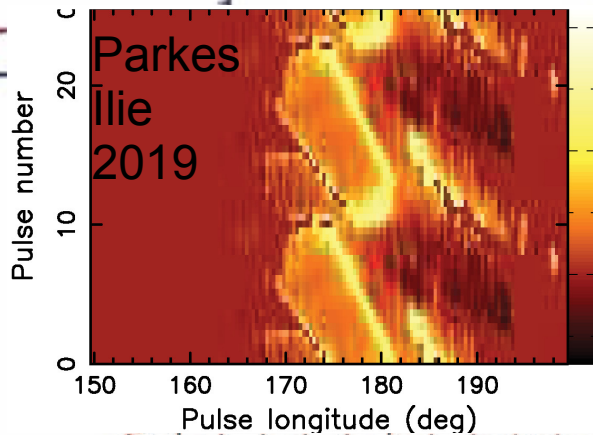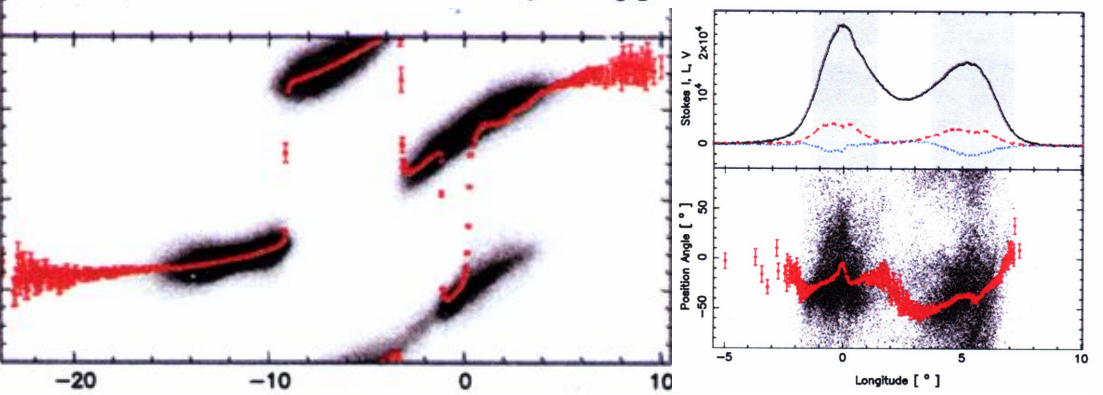
Jarek Dyks

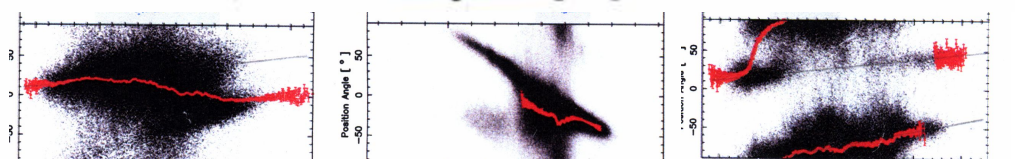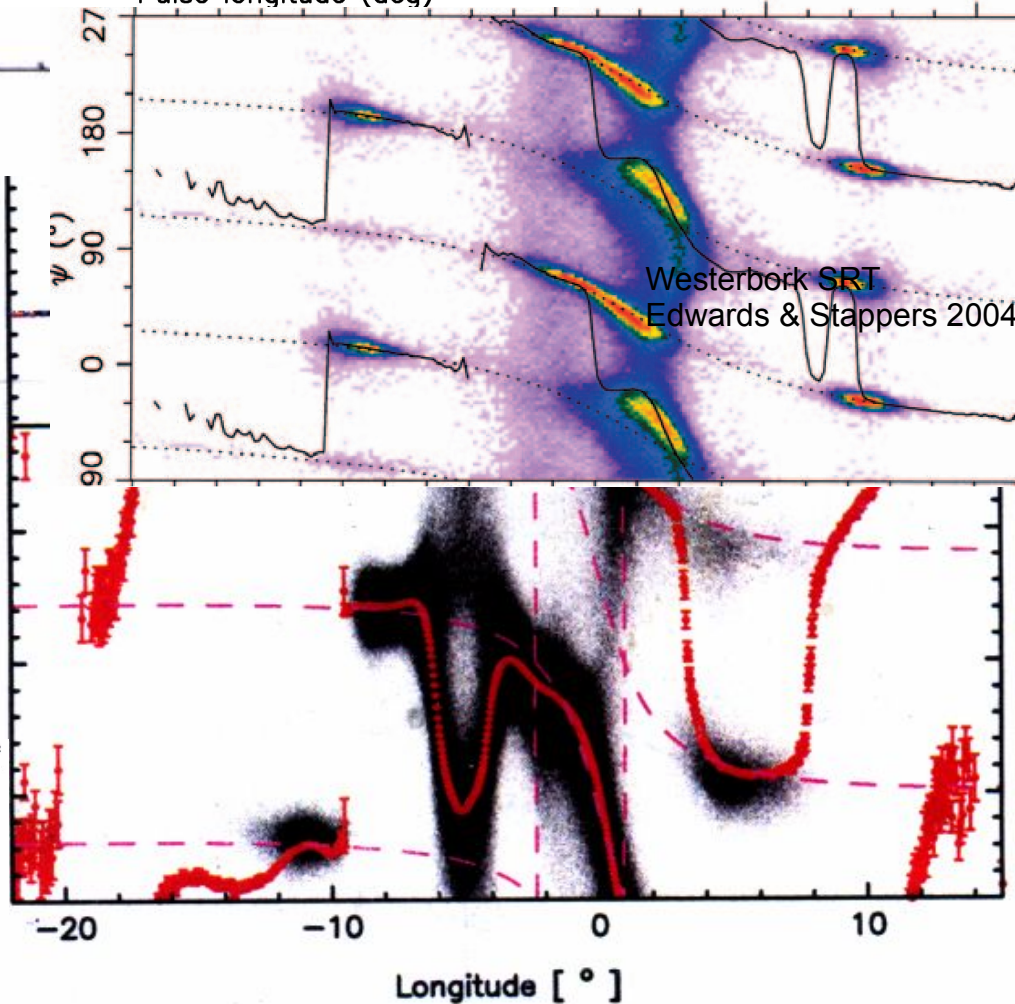Nicolaus Copernicus Astronomical Center
Polish Academy of Sciences
Toruń

Parkes
Ilie
2019

Arecibo Observatory,
Mitra, Rankin,
Arjunwadkar 2015,
2016, SRM13, HR10

Westerbork SRT
Edwards & Stappers 2004
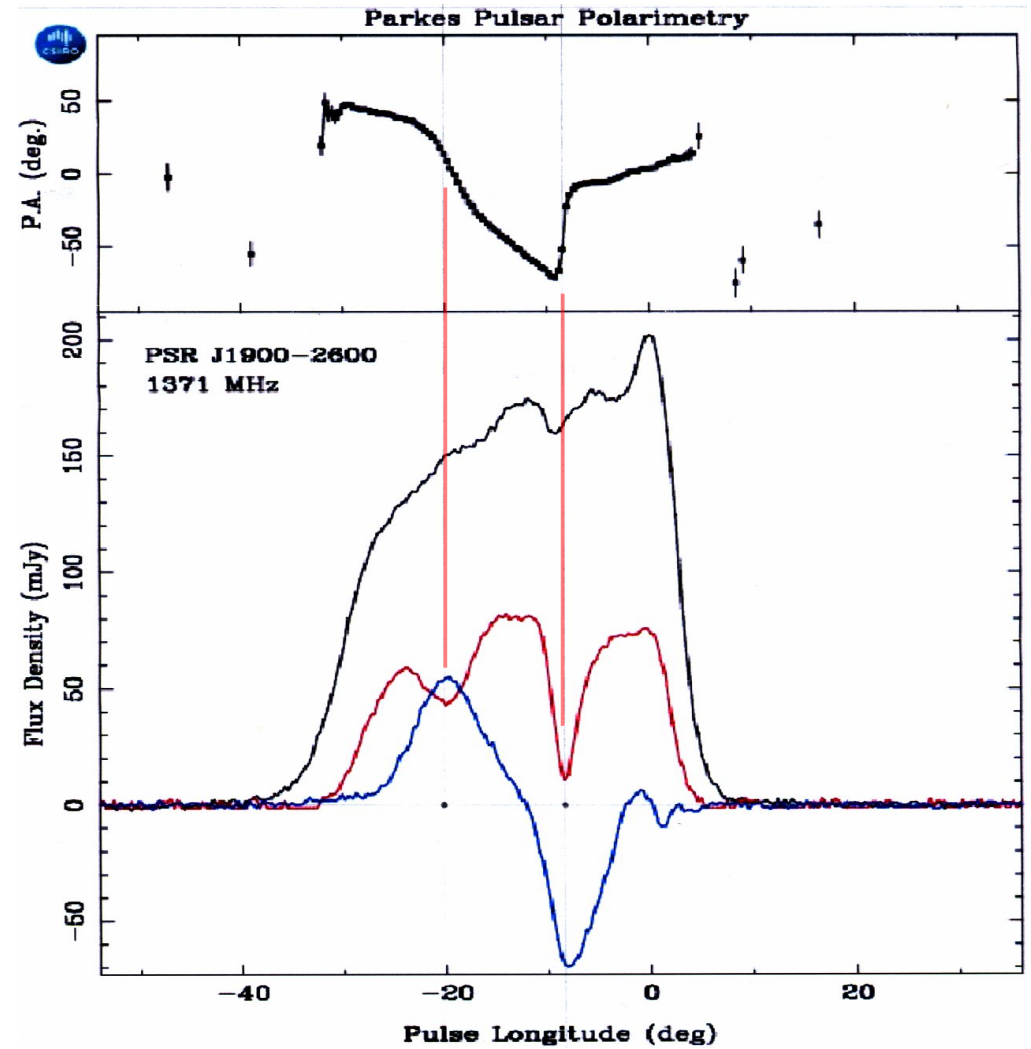
B0834+06   Arecibo 1220.67 MHz 1.274 s   RM: 23.600 rad m⁻²
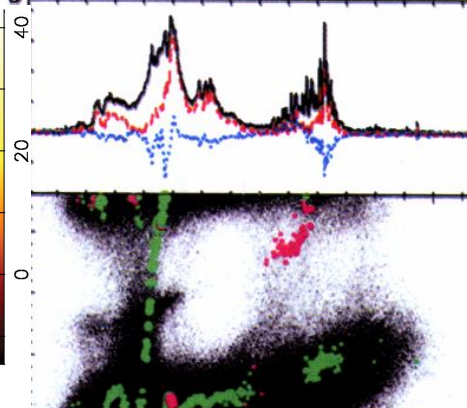
Orthogonal jumps of polarisation angle (PA) at maximum V
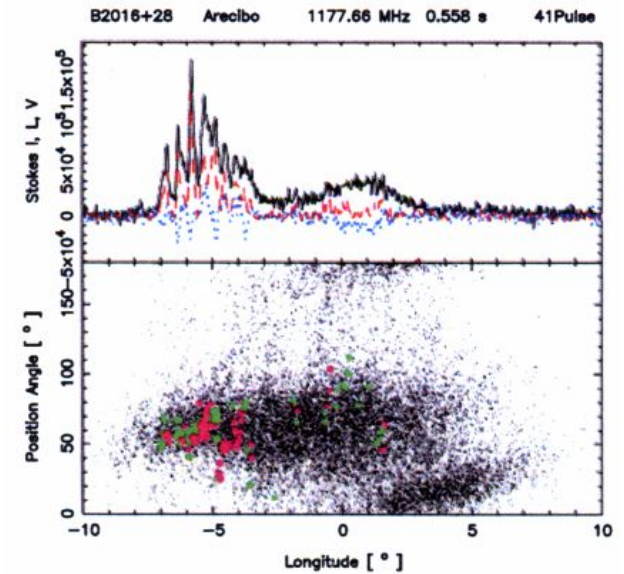## PA flat beyond jumps
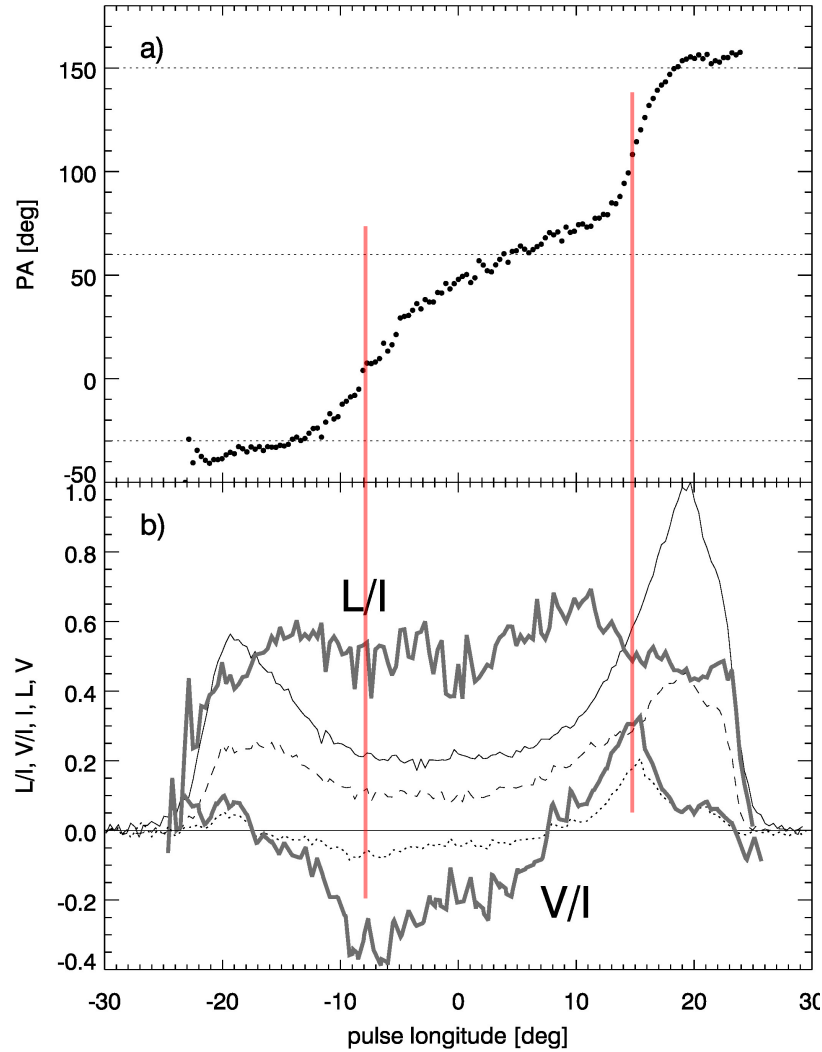
B1913+16, Weisberg & Taylor 2002;

J1900-2600, Johnston & Kerr 2017

Each polarisation mode exhibits both signs of V
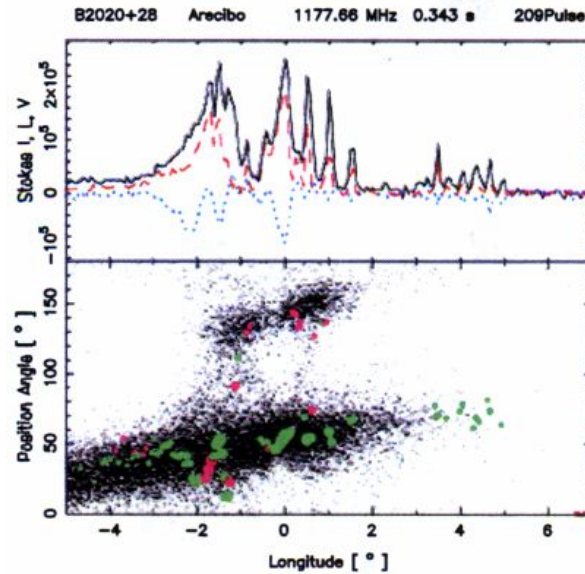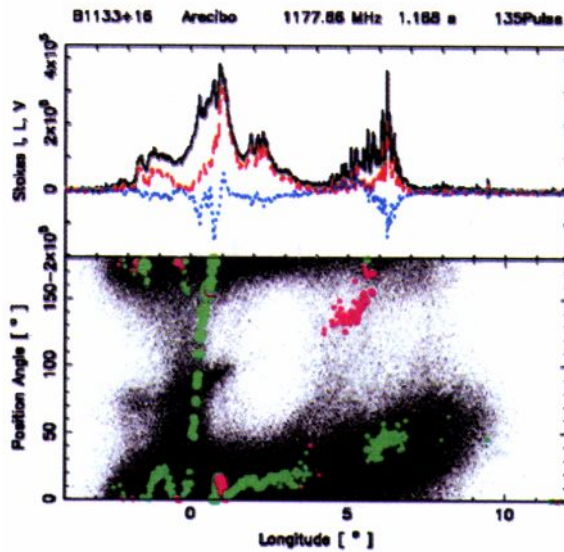
Single pulse (real time) data

Red dots: positive V
Green dots: negative V

(Mitra et al. 2015)

??

Bifurcations and distortions of PA tracks from RVM model
(RVM = based on direction of sky-projected B)

again with OPM transitions at high |V|

and with sign-changing V at considerable L

B1237+25 Smith et al. 2013
B1933+16, Mitra et al. 2016

Coherent emission of two modes and V in strong B improbable

Possibly **mode coupling at polarization limiting radius** Cheng & Ruderman 1979
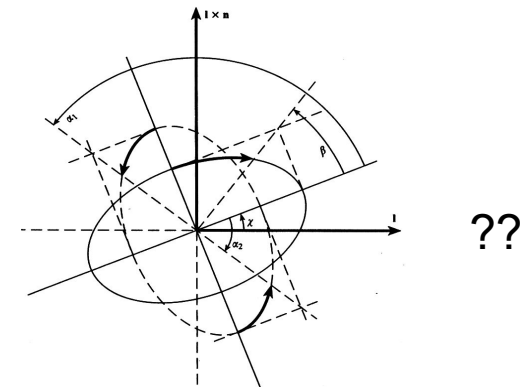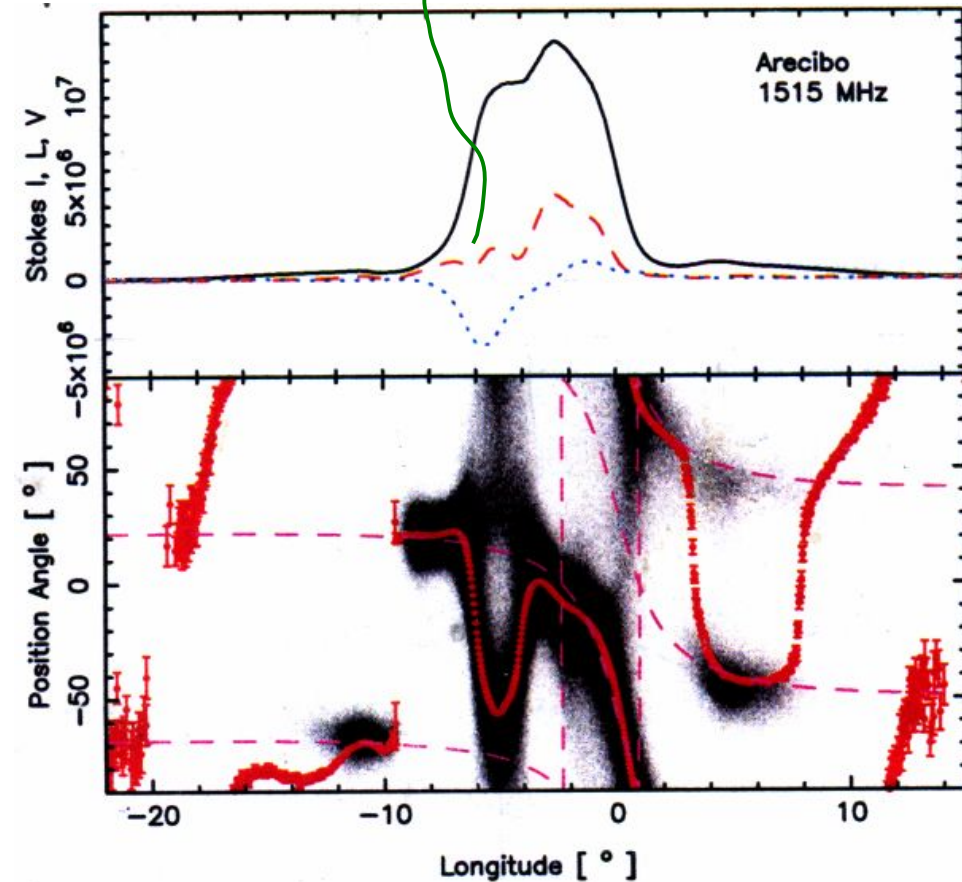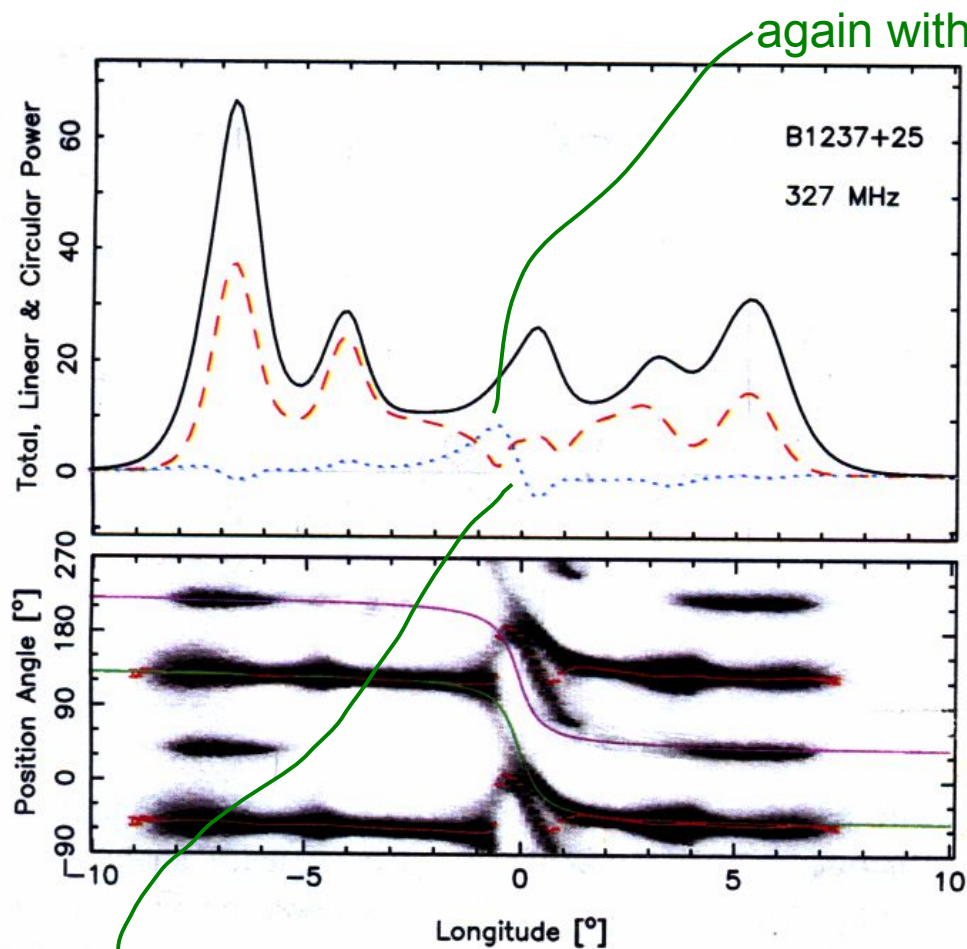
Mode leaking due to growing scale of intermodal beating
(large w.r.t. scale of medium non-uniformity)

Solution of evolution equation for plasma-wave system necessary

Lyubarsky & Petrova 1999 – approximate analytical estimates:

First principle results:
  - **rough (analytical)**
  - **specific (numerical)**

constant handedness, symmetrical V/I, or
constant V (and handedness)

Beskin, Philippov 2012, Petrova, Lyubarsky 2000, Wang, Lai & Han 2010 – specific numerical results:

one max-V OPM jump at specific viewing angle

Impressive calculi but results bear vague resemblance to the observed polarized profiles

Empirical way: addition (superposition) of OPMs
        - noncoherent, selected longitudes, McKinnon 2003, Melrose et al. 2006, Karastergiou 2009
        - coherent, single longitude, Kennett & Melrose 1998, Edwards & Stappers 2004

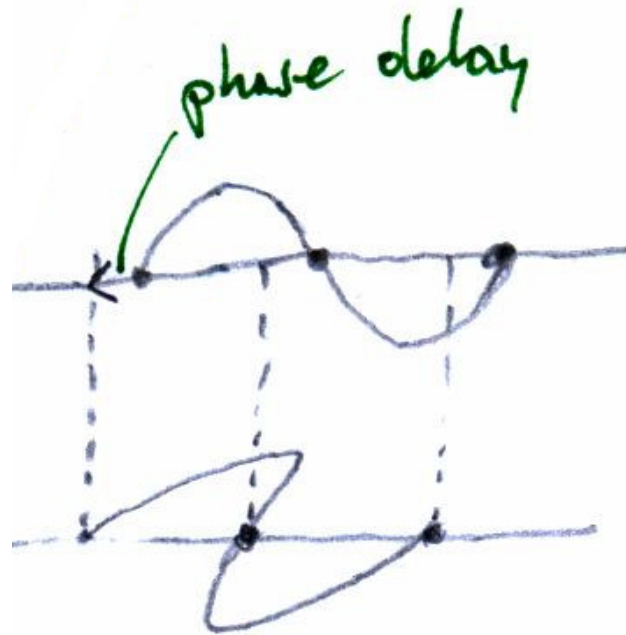The model: coherent sum of orthogonally polarized waves
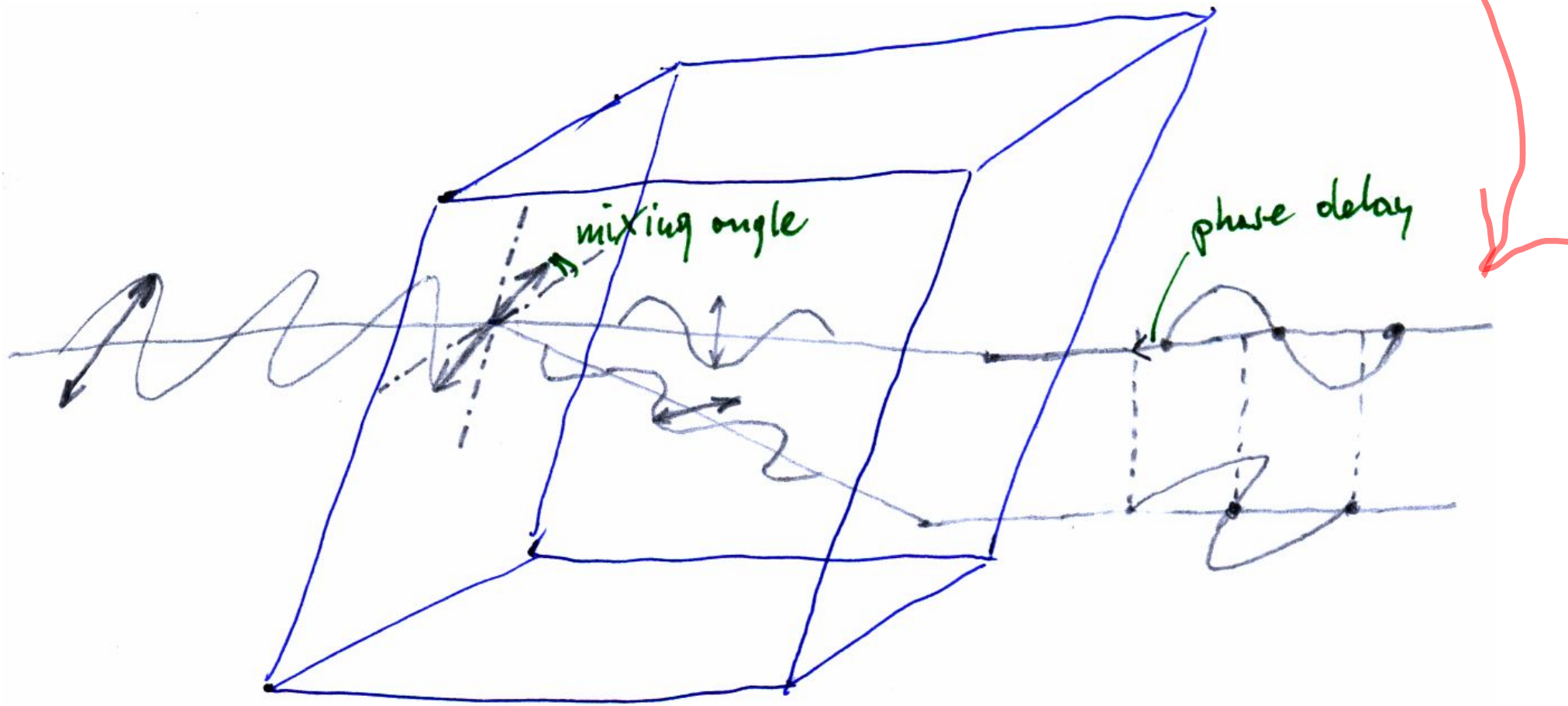
- mode amplitude ratio **MAR**   or   mixing angle **MA** $\tan(\textbf{MA}) = E2/E1$
- phase lag **PhLg**   **MA = 45 deg => E2 = E1**
- eccentricity of polarization ellipse

+ distribution widths

The model: **coherent sum of orthogonally oscillating sinusoids**

- mode amplitude ratio **MAR**   or   mixing angle **MA**   **tan(MA) = E2/E1**

- phase lag **PhLg**   **MA = 45 deg => E2 = E1**

- eccentricity of polarization ellipse   (3 parameters)

+ widths of their statstical distributions (6 parameters)

Some parameters partially covariant (degenerate), e.g.:

- mode amplitude ratio
- phase lag

- width of phase lag distribution
- peak position of phase lag distribution

Multiple interpretations possible

=> useful to simultaneously consider:

- polarization within a pulse **longitude interval**
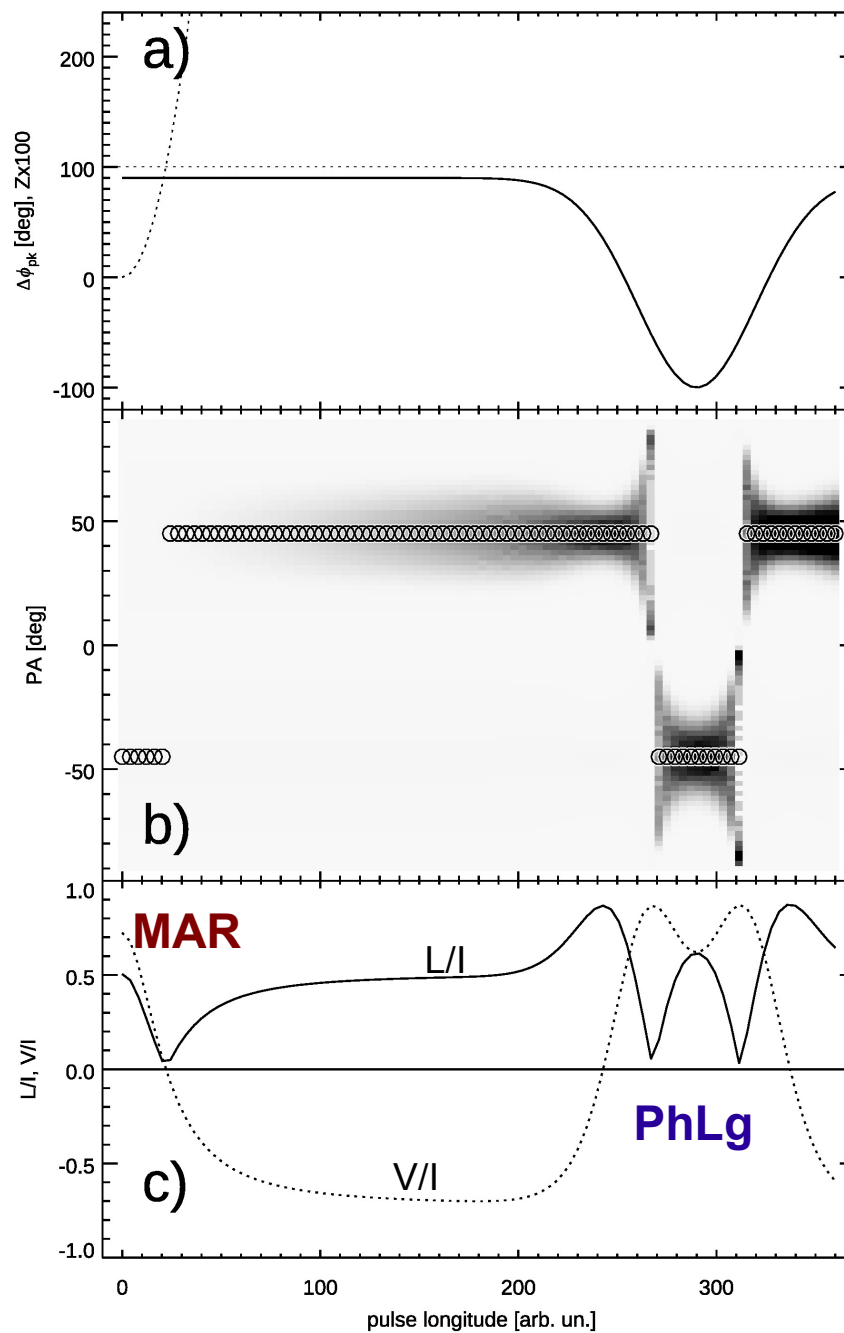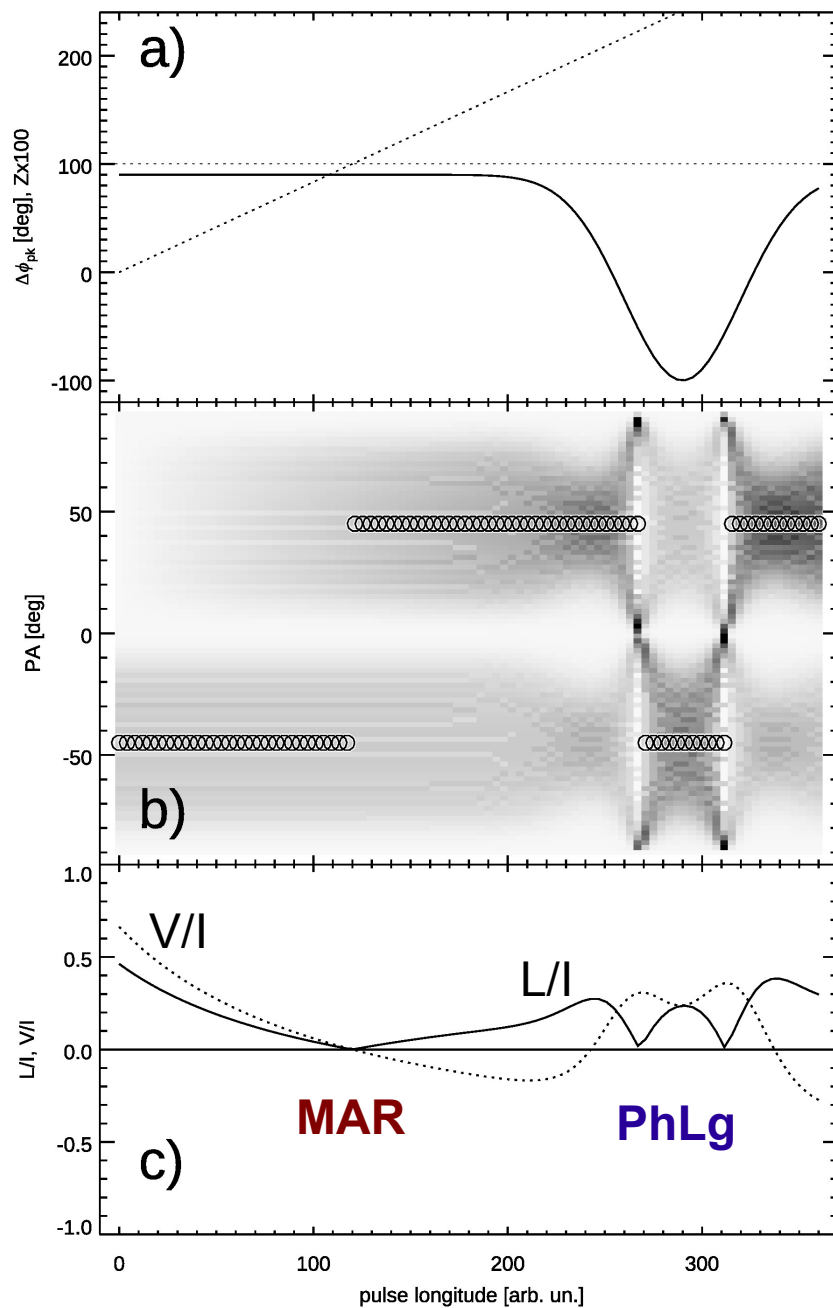
- **different frequencies** nu

to break the degeneracy

=> additional parameters for pulse-longitude profiles of the basic parameters

Two main effects: **MAR**: mode amount ratio (regular OPM jumps)

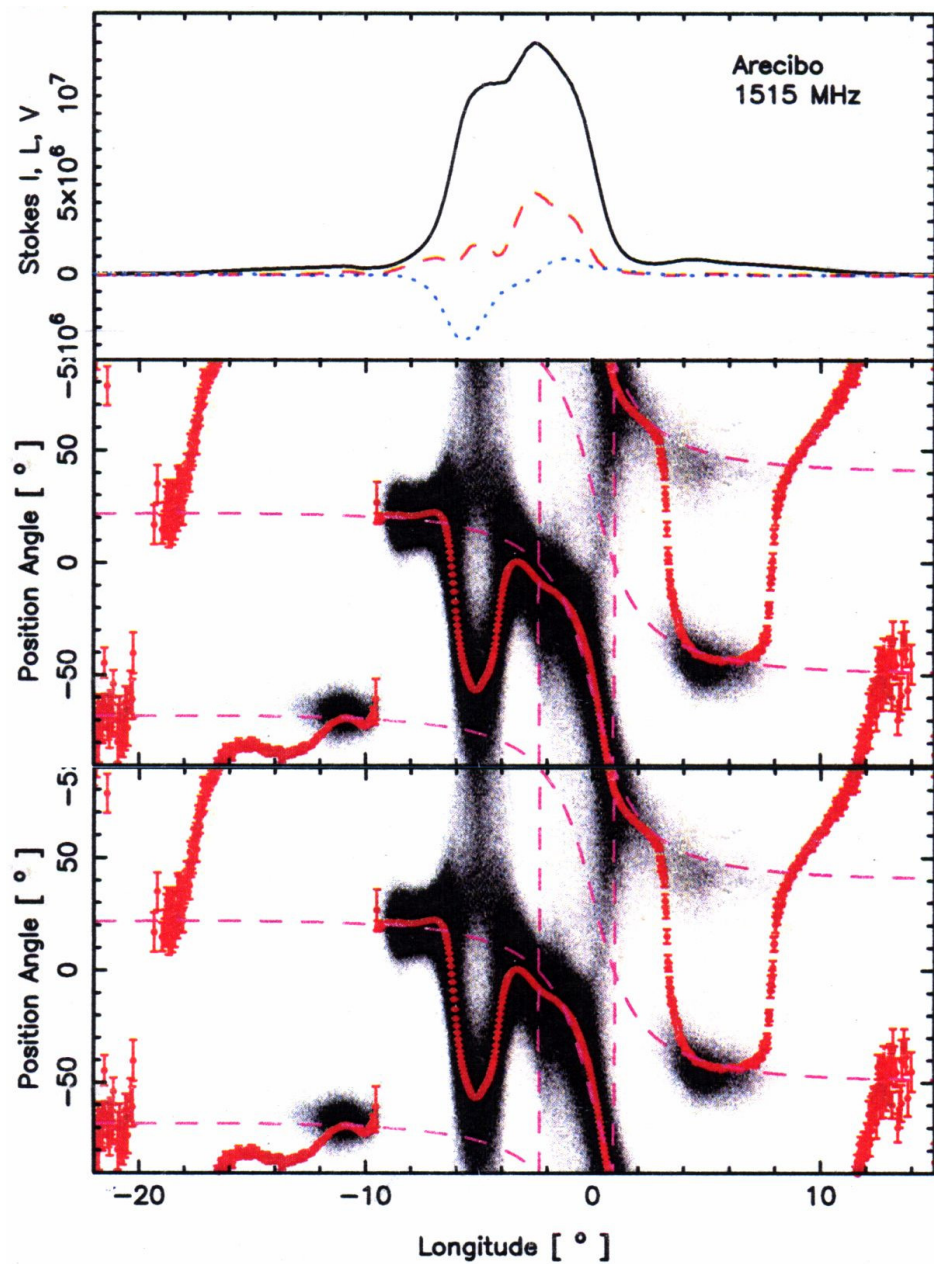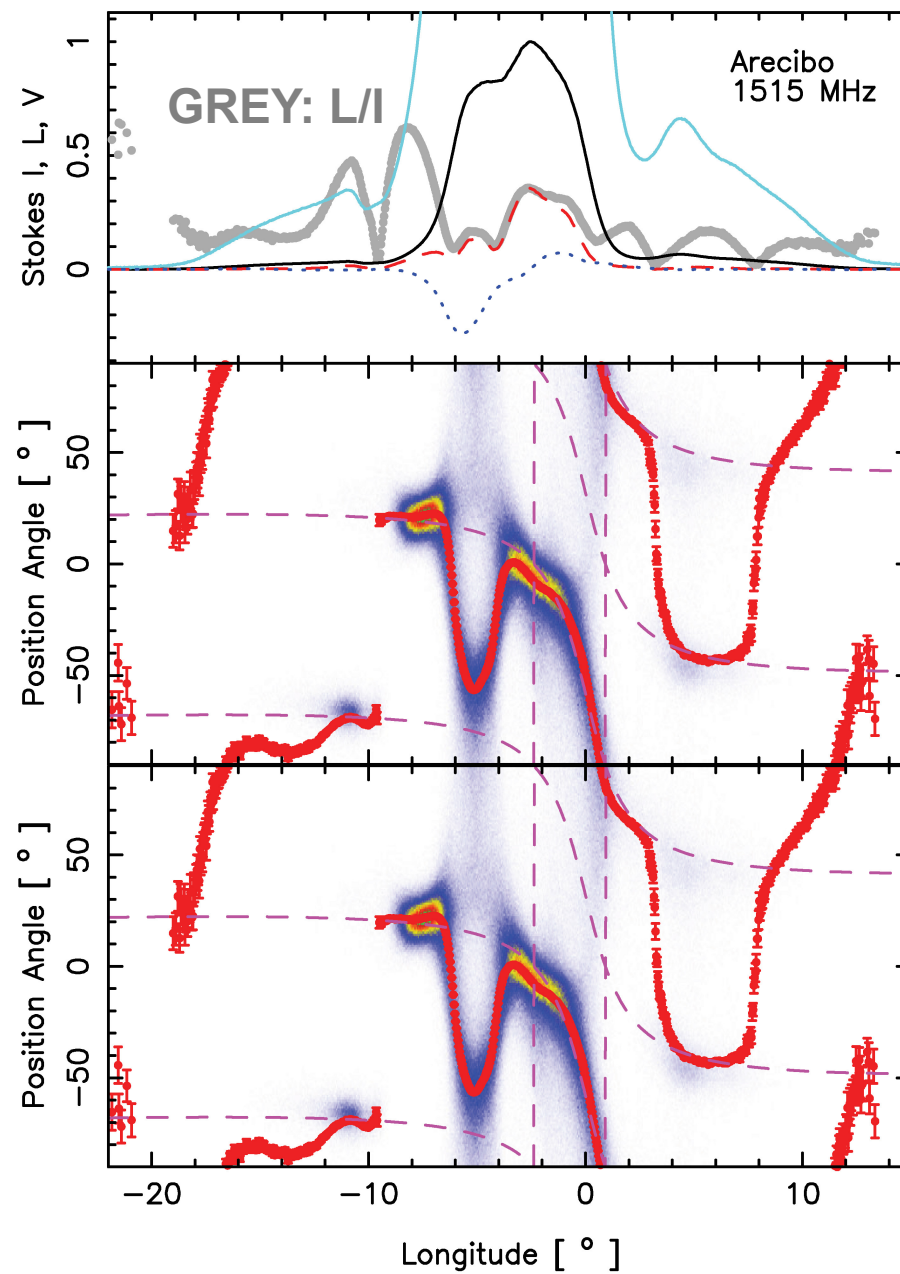**PhLg**: phase lag (quarter-wave plate effects, max-V OPM jumps)

B1933+16

PA loop with `**tongue and horns**'
+ twin minima in L/I

1.5 GHz

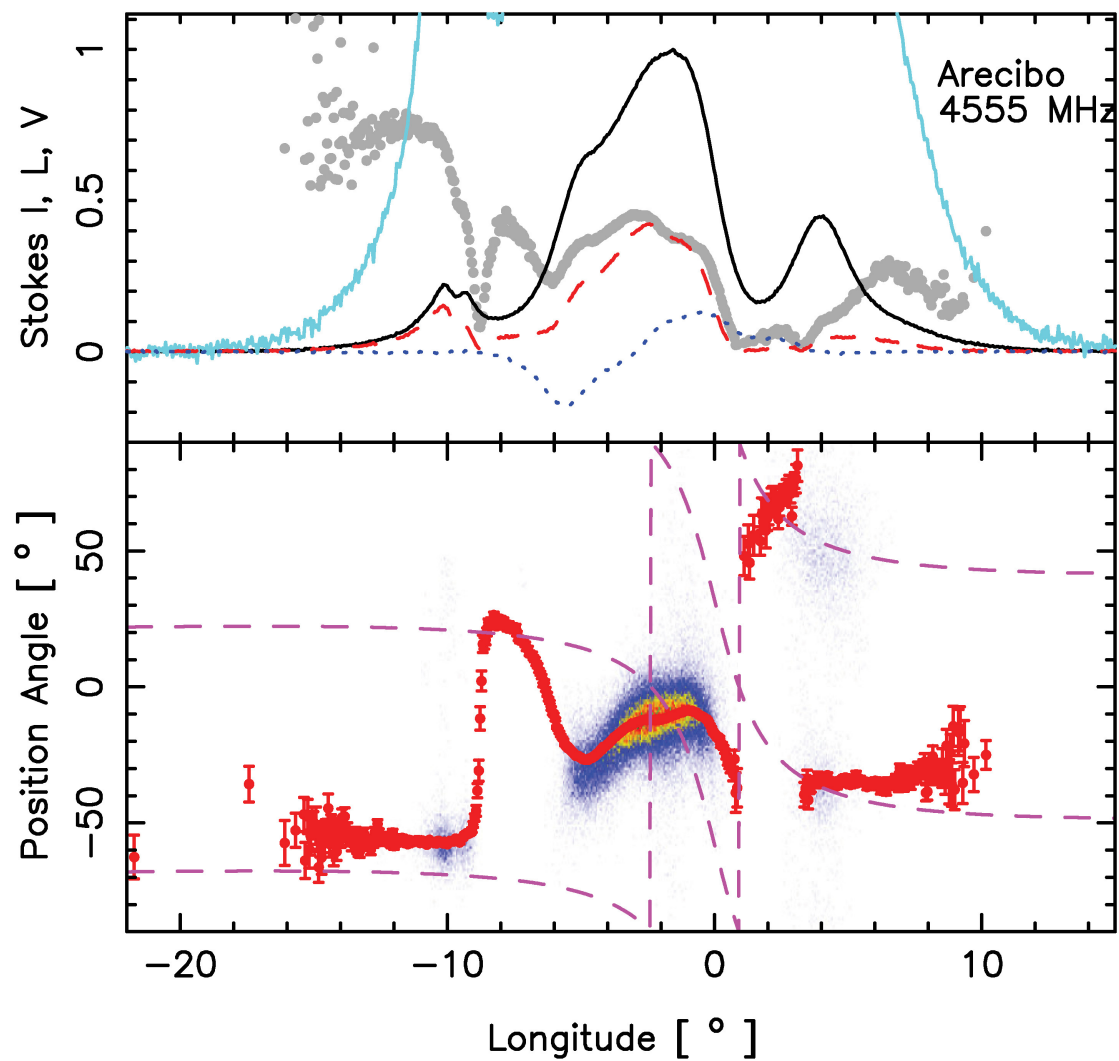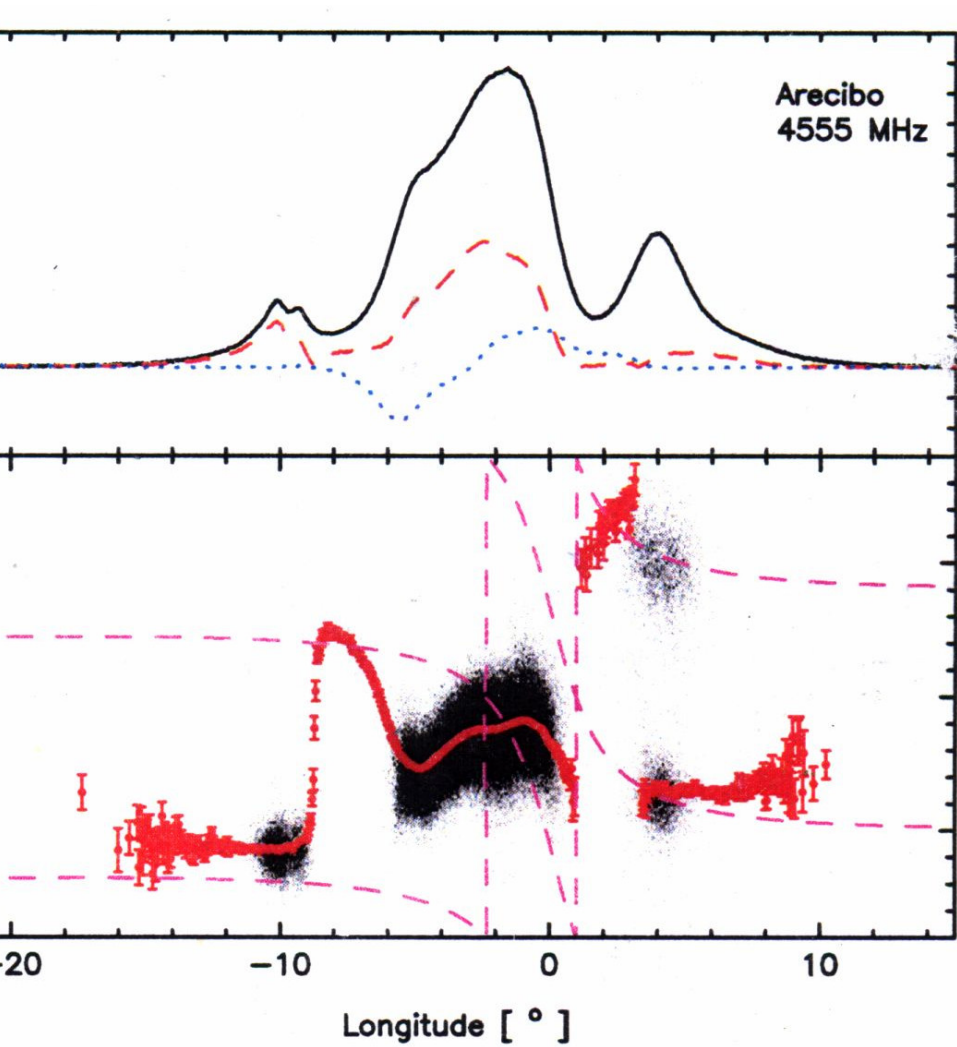Arecibo, Mitra, Rankin, Arjunwadkar 2016

MAR inverted several times

B1933+16   Same feature   **4.5 GHz**

No PA bifurcation, U-shaped PA
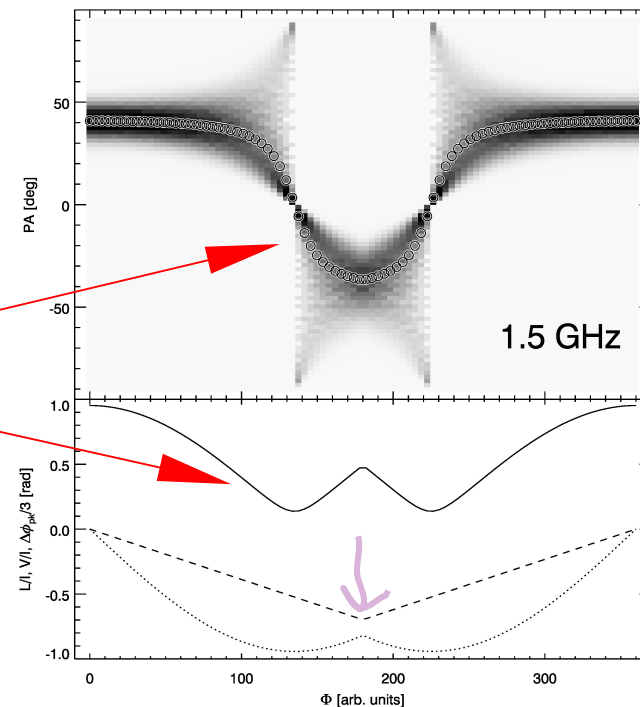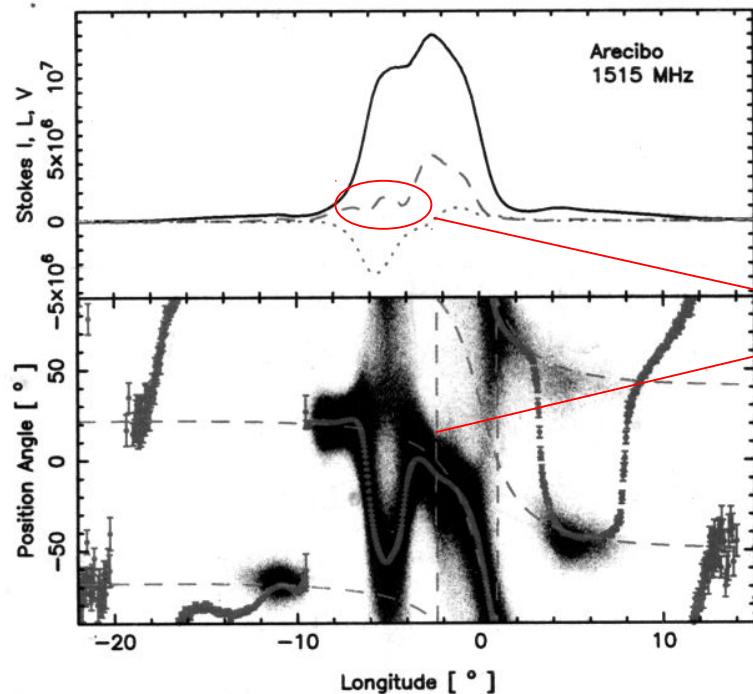

Mitra et al. 2016

Multiple interpretations possible: **Mixing angle = f(Phi)**   Phi = pulse longitude

Any PA distortions + twin minima in L/I but **no bifurcations**
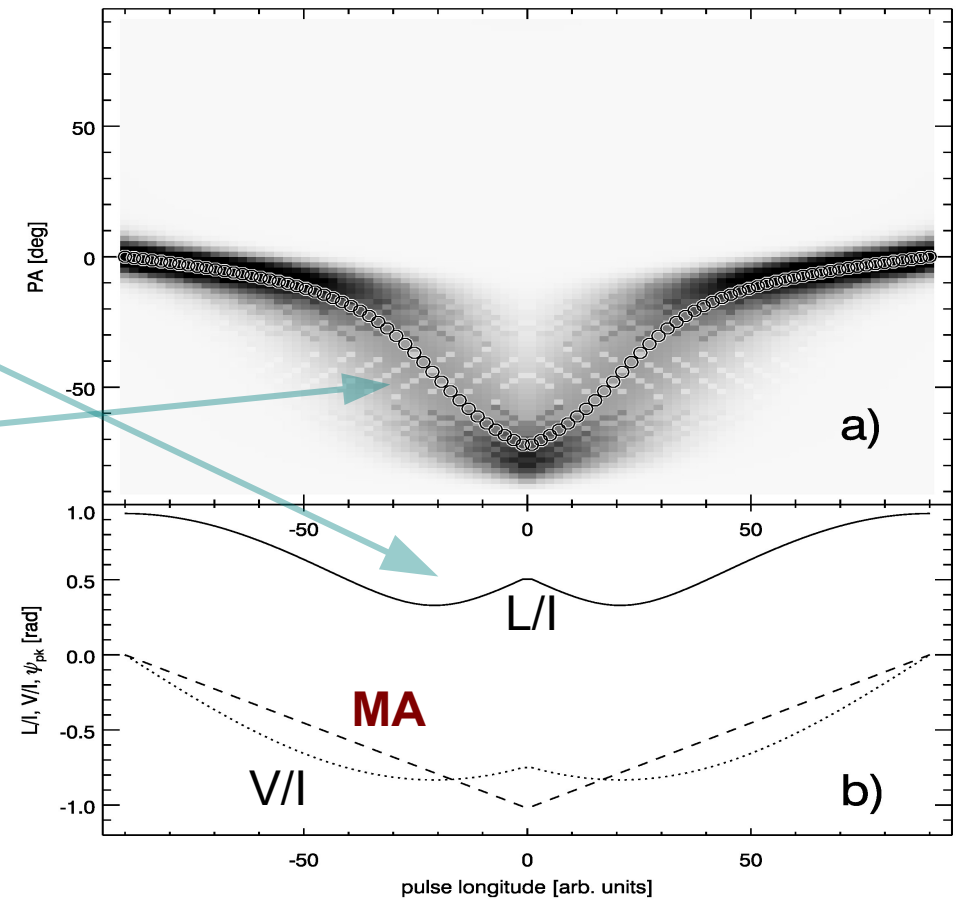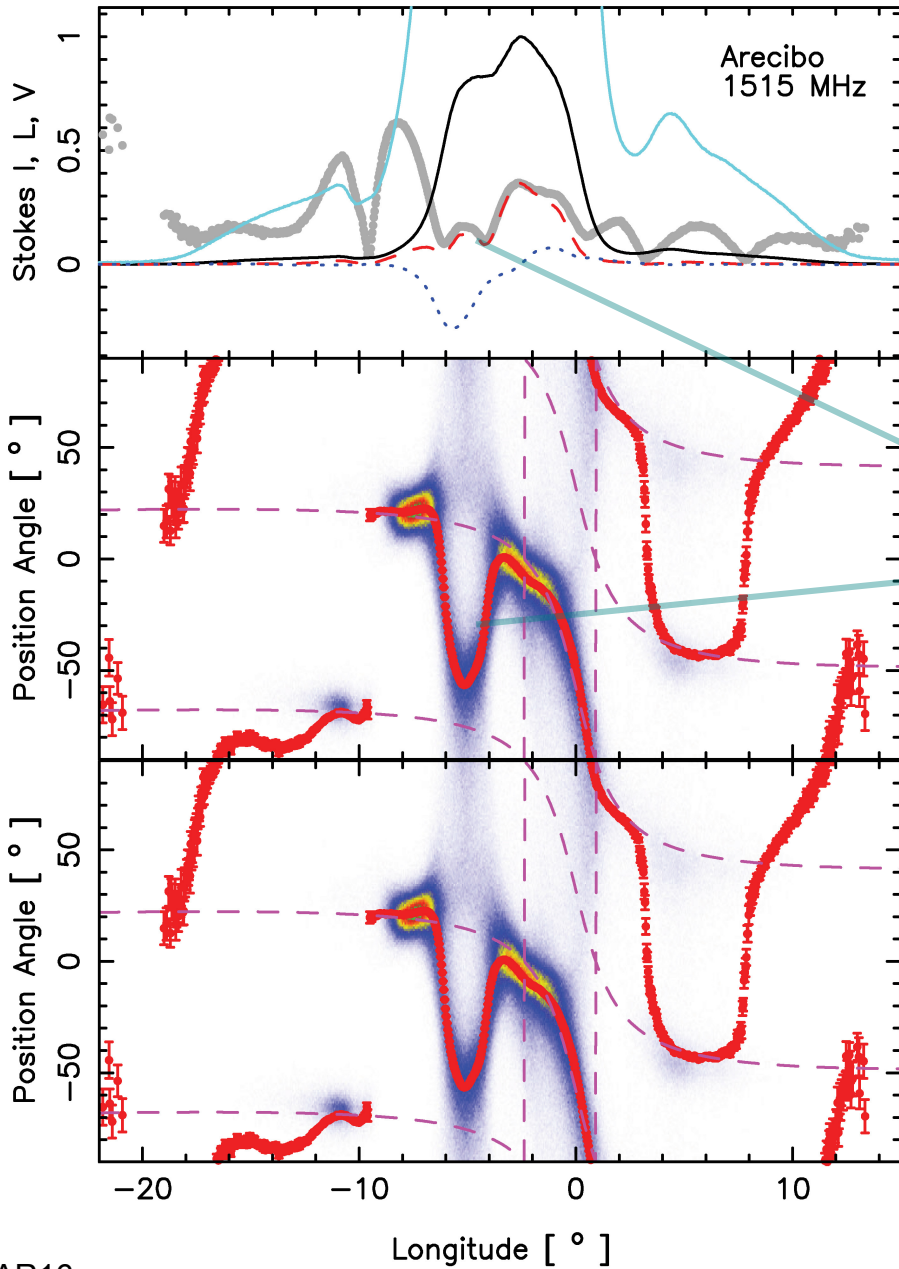
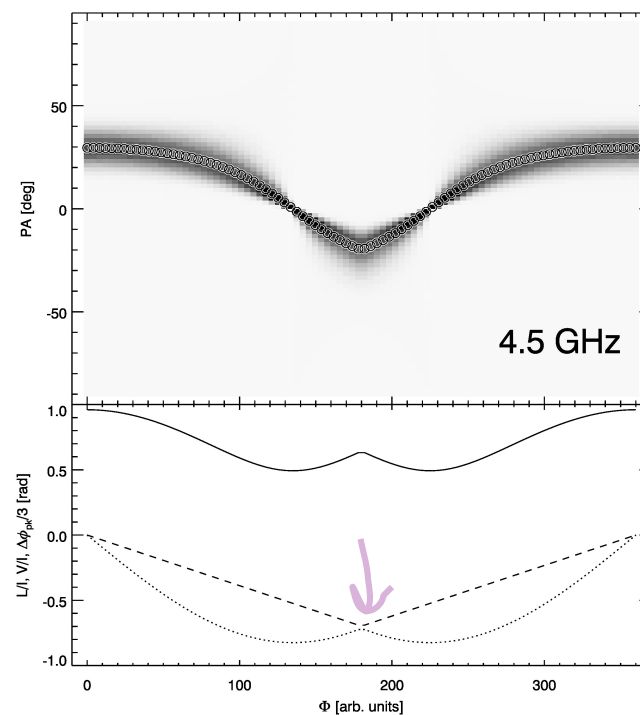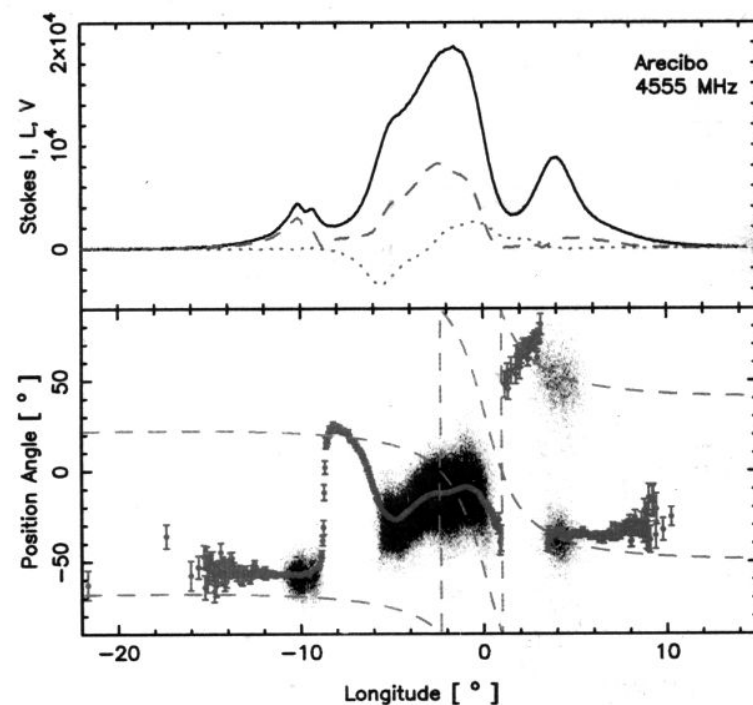# Multiple interpretations possible: phase lag = f(Phi)   longitude-dependent lag

Mitra et al. 2016

Dyks 2017

Model works at both nu
if **MA** = f(nu)
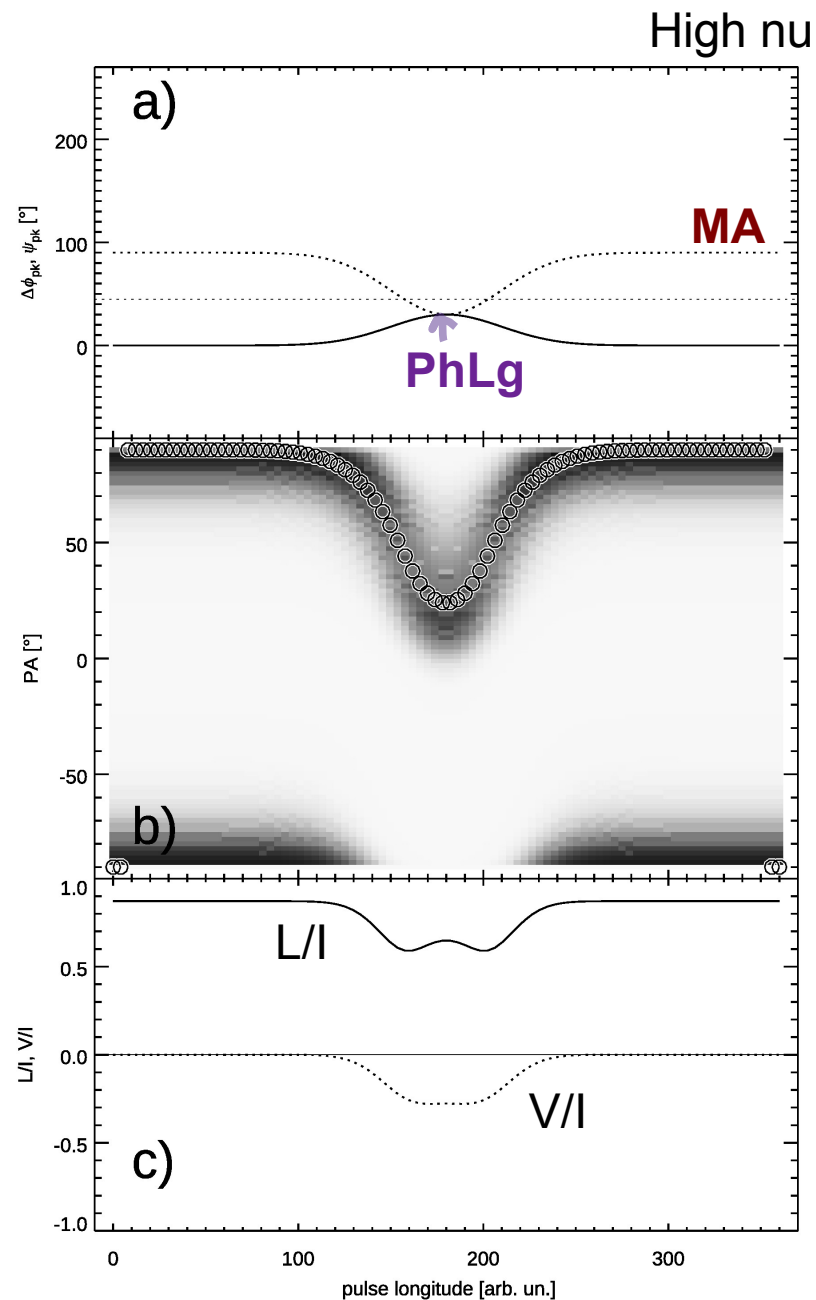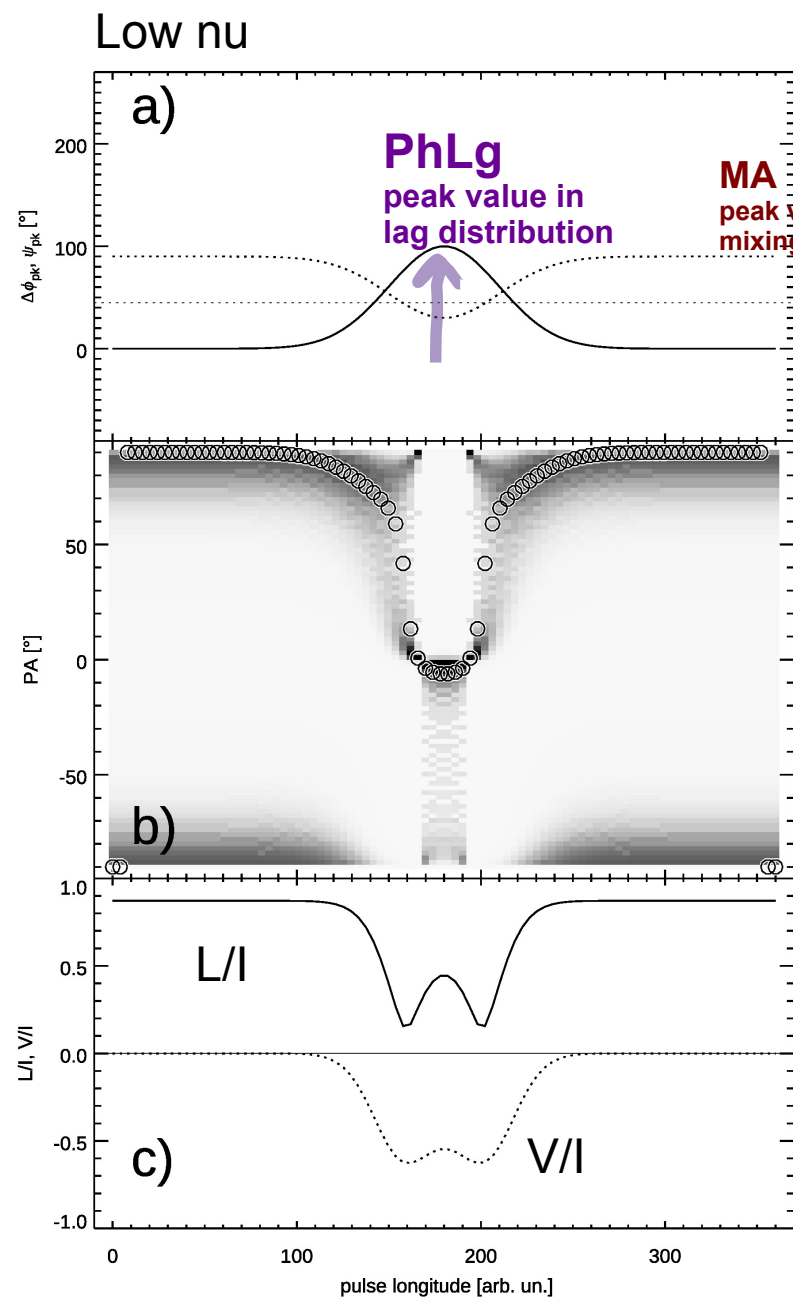
Features reproduced:

- PA loop / U-distort.
- twin minima in L/I
- large V/I

HOWEVER:

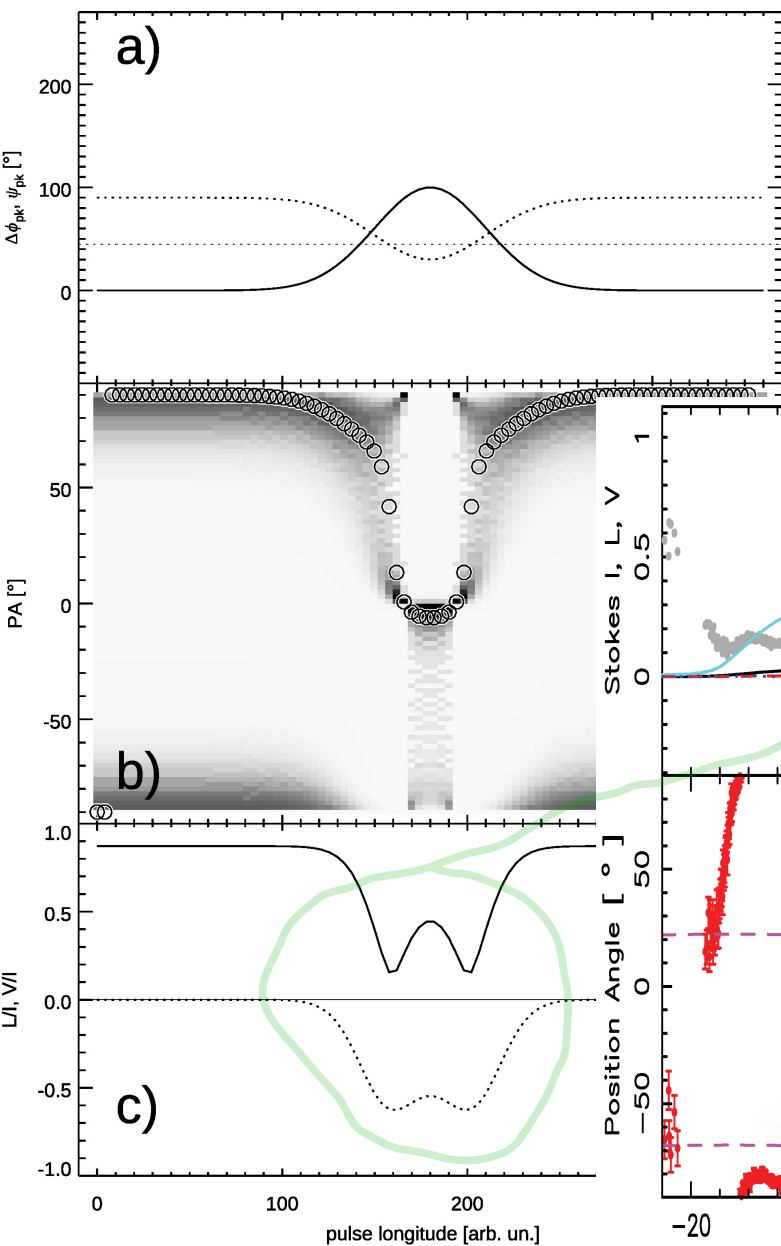Missing tongue
same lag amplitude needed at both nu

Longitude-dependent **mixing angle** and **phase lag** (all other parameters fixed)
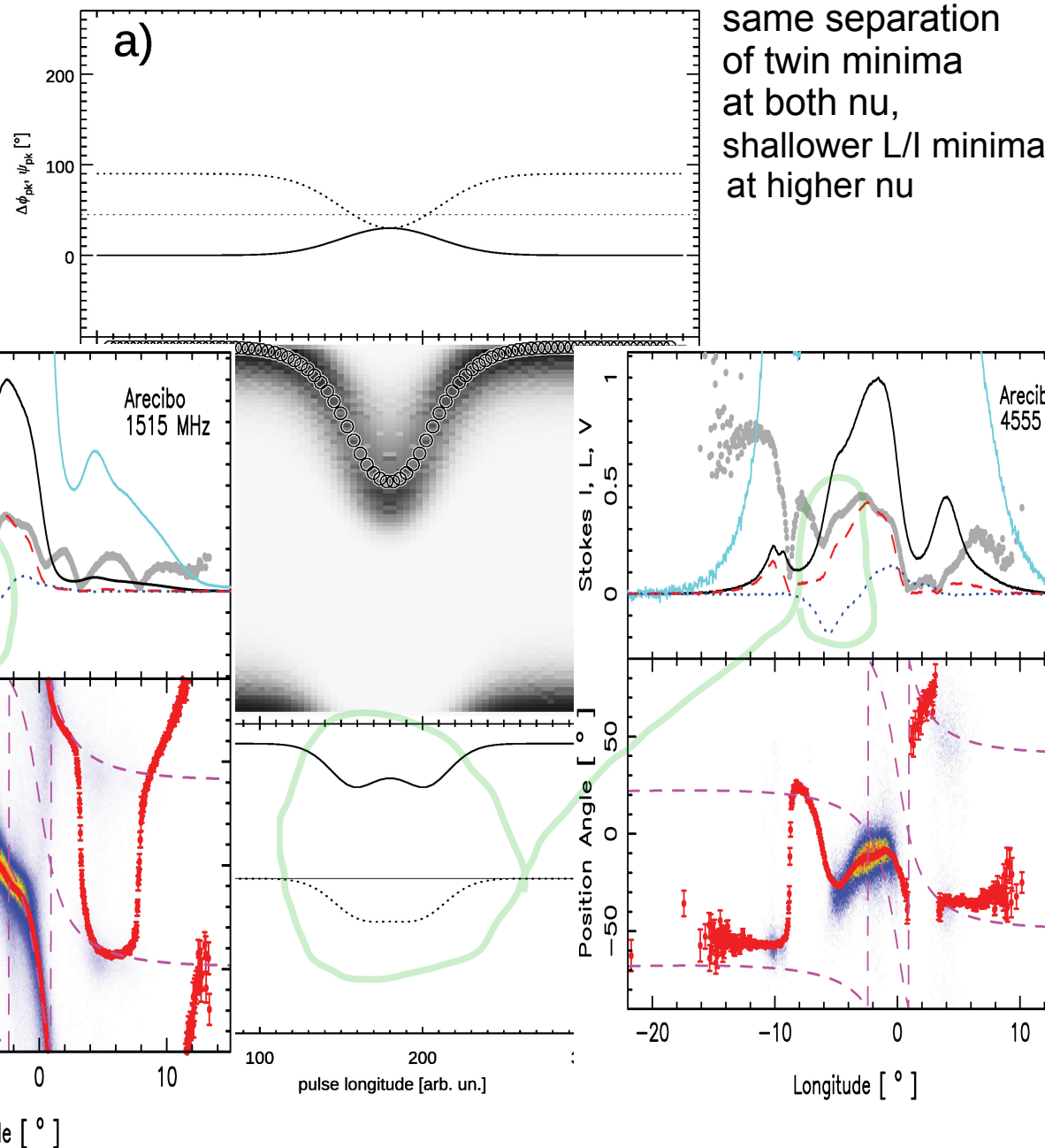Phase lag amplitude smaller at high nu

Dyks 2019

Longitude-dependent mixing angle and phase lag
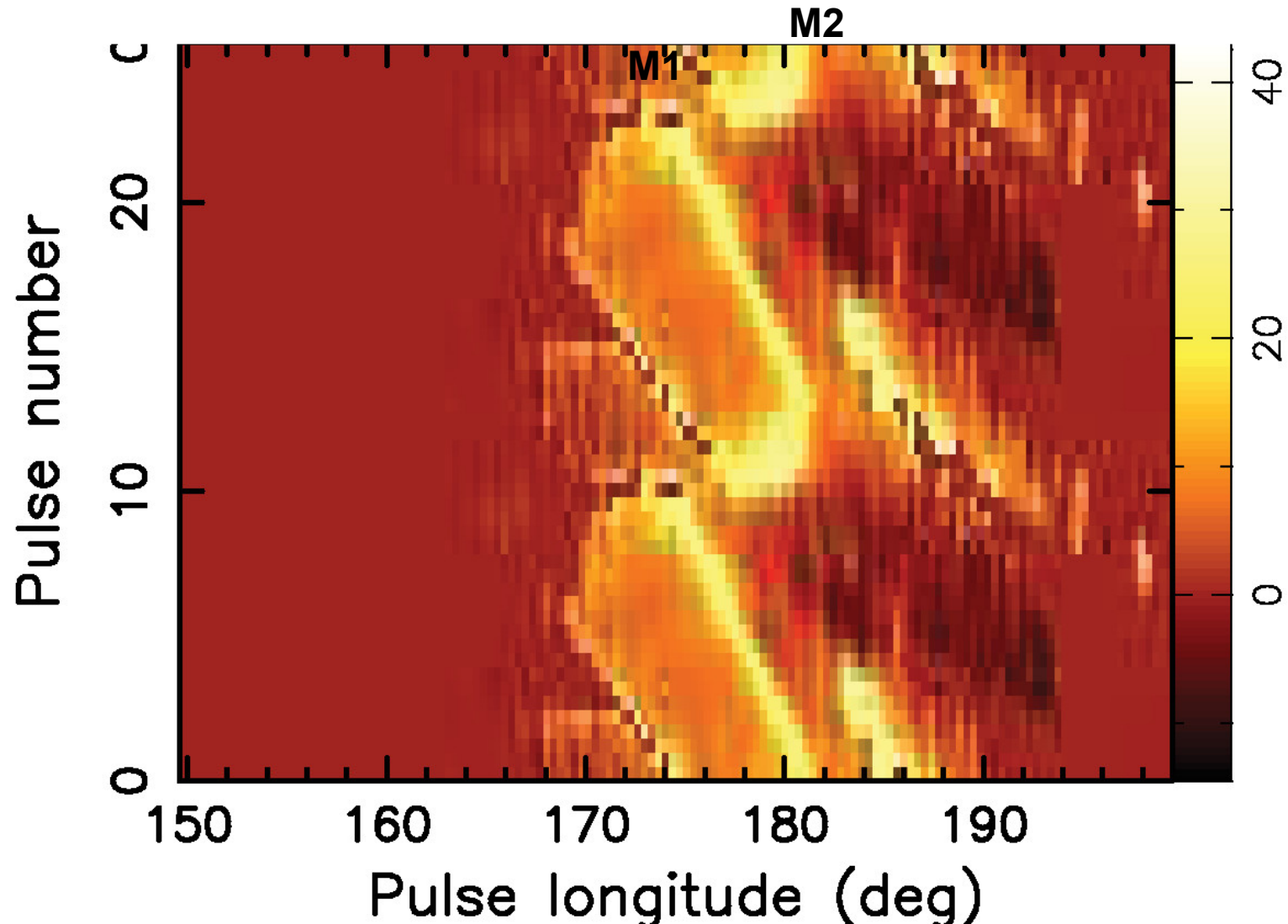## Phase lag amplitude smaller at high nu

Reproduced features:
PA loop/U, twin min. in L/I, single sign V,
relative amount of L/I and V/I at both nu,
same separation
of twin minima
at both nu,
shallower L/I minima
 at higher nu

a)

a)

b)

c)

Arecibo
1515 MHz

Arecib
4555

High V from coherent mode superposition
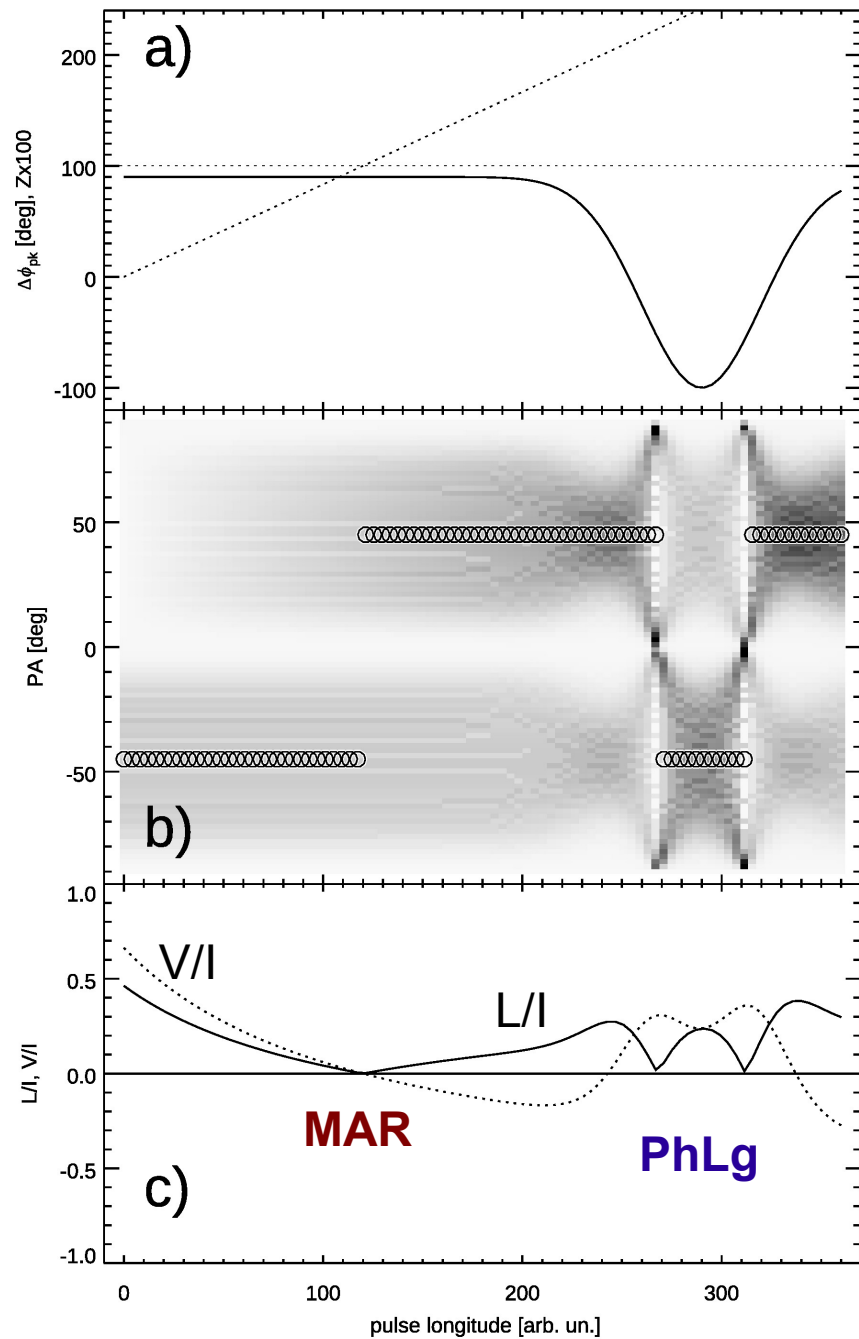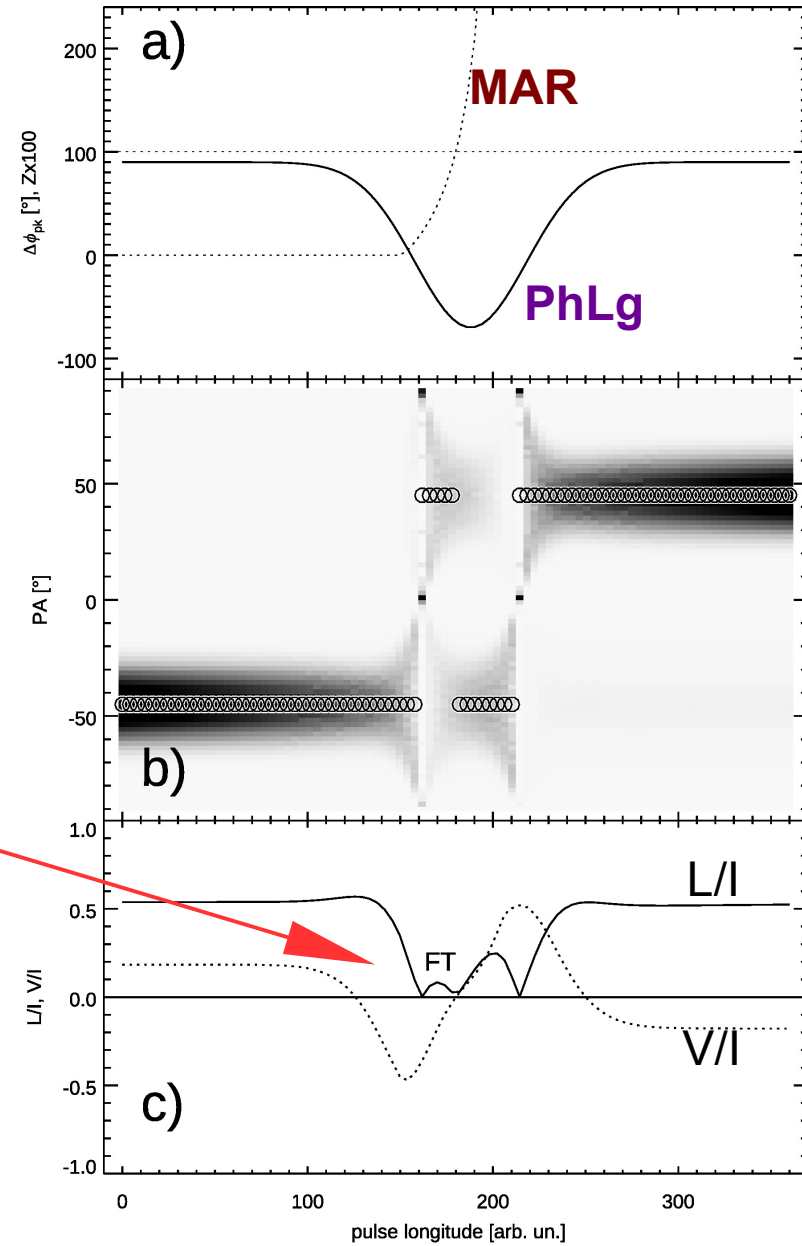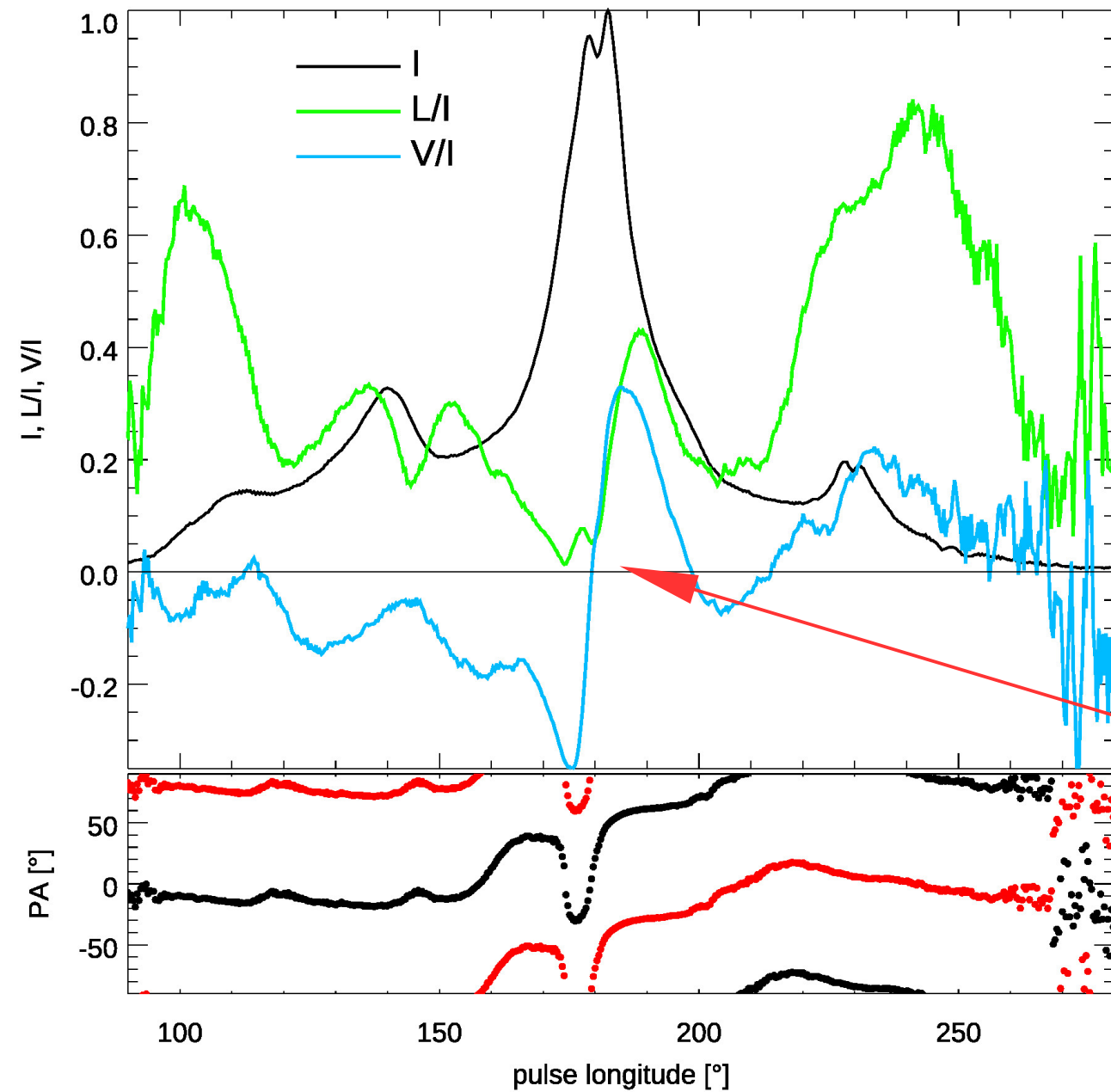

Yellow rim = high circular

= large eccentricity angle (= small eccentricity of polarization ellipse)
(= circularly polarized wave)

What if **asymmetric** profiles of **MAR** (mode amount ratio) and **PhLg (**phase lag) overlap?
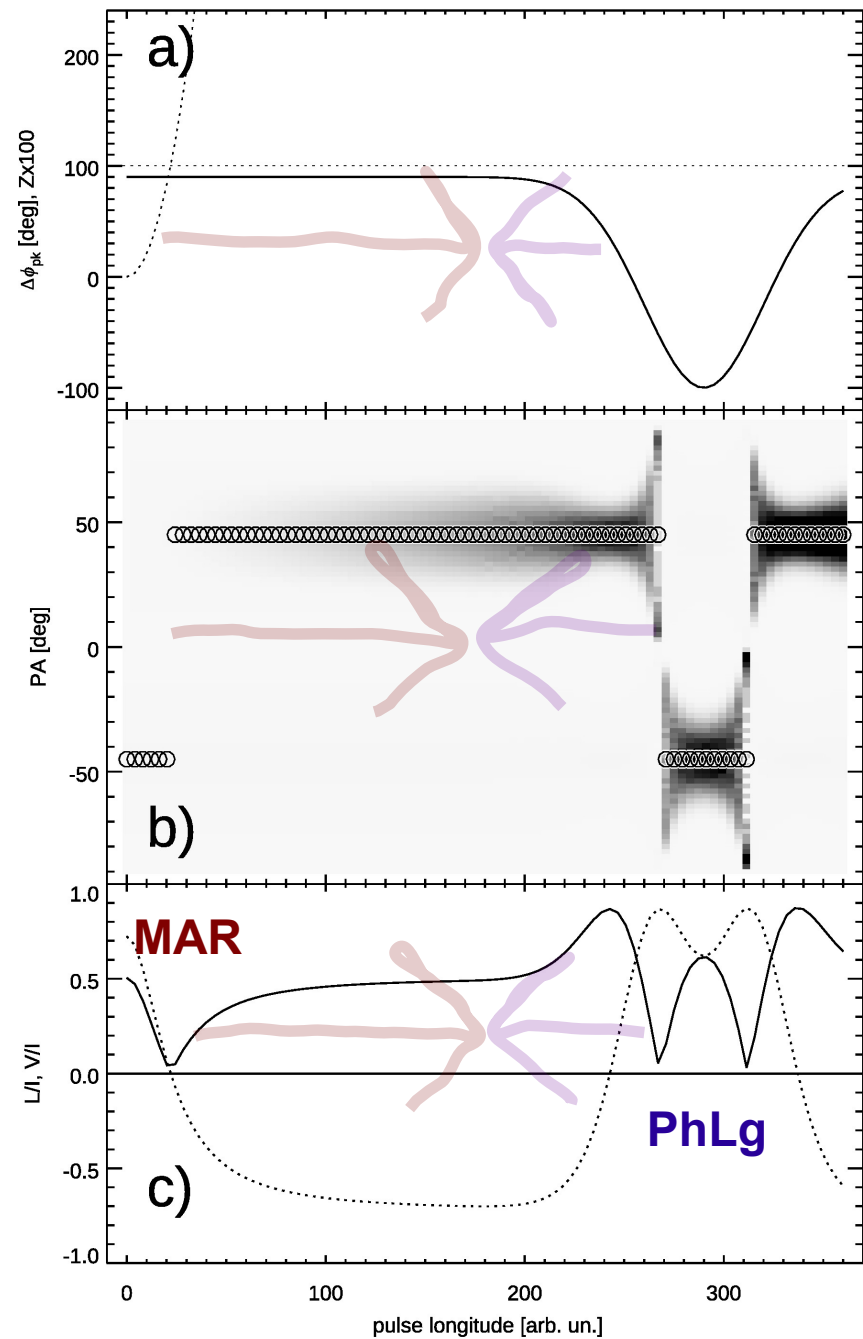
Antisymmetric **MAR** + symmetric **PhLg** (not perfectly aligned)

Dyks 2019

J0437-4715, 660 MHz, Navarro et al. 1997
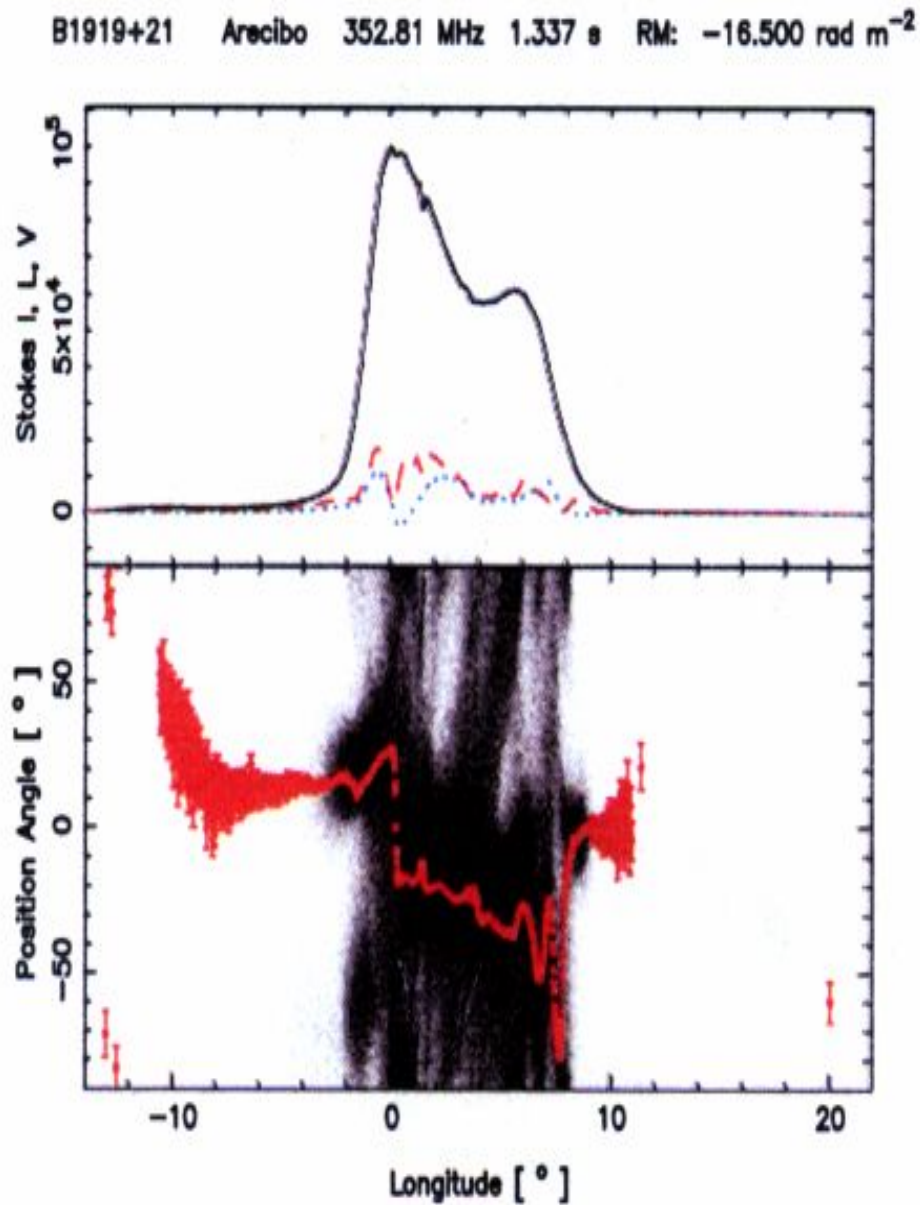
45 deg PA jumps: You have two orthogonal things, either one can dominate, whence the 45 degrees?   way out: add the modes coherently
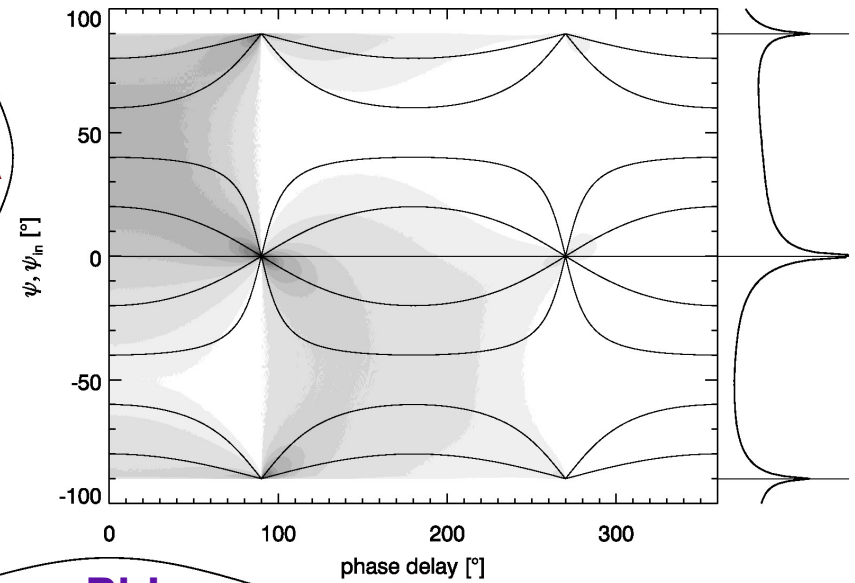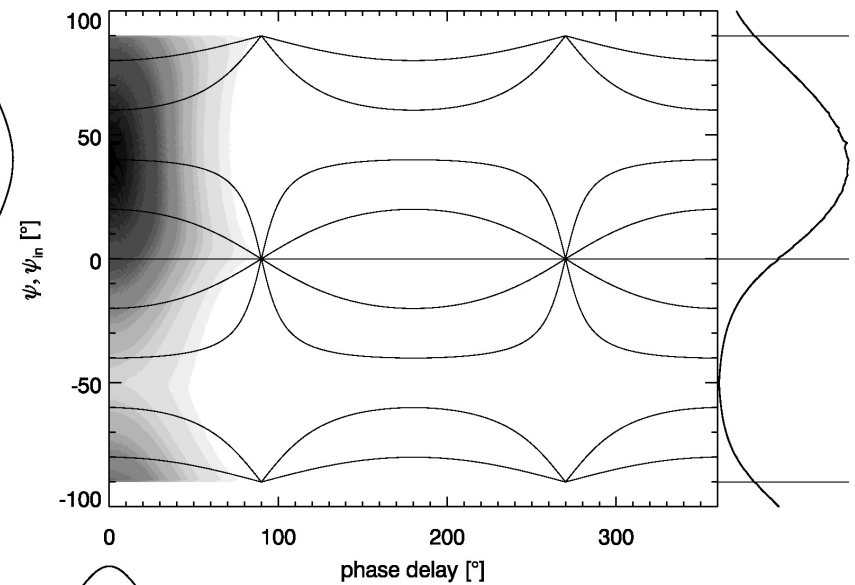

Mitra, Arjunwadkar, Rankin 2015

Everett & Weisberg 2001

45 deg PA jump

MAG. POLE   SYMMETRY POLE

AT EMISSION RADIUS   AT PLR

Δ_{plr}

β

SIGHTLINE PATH

(pulse lonfitude)

ψ_{pk}
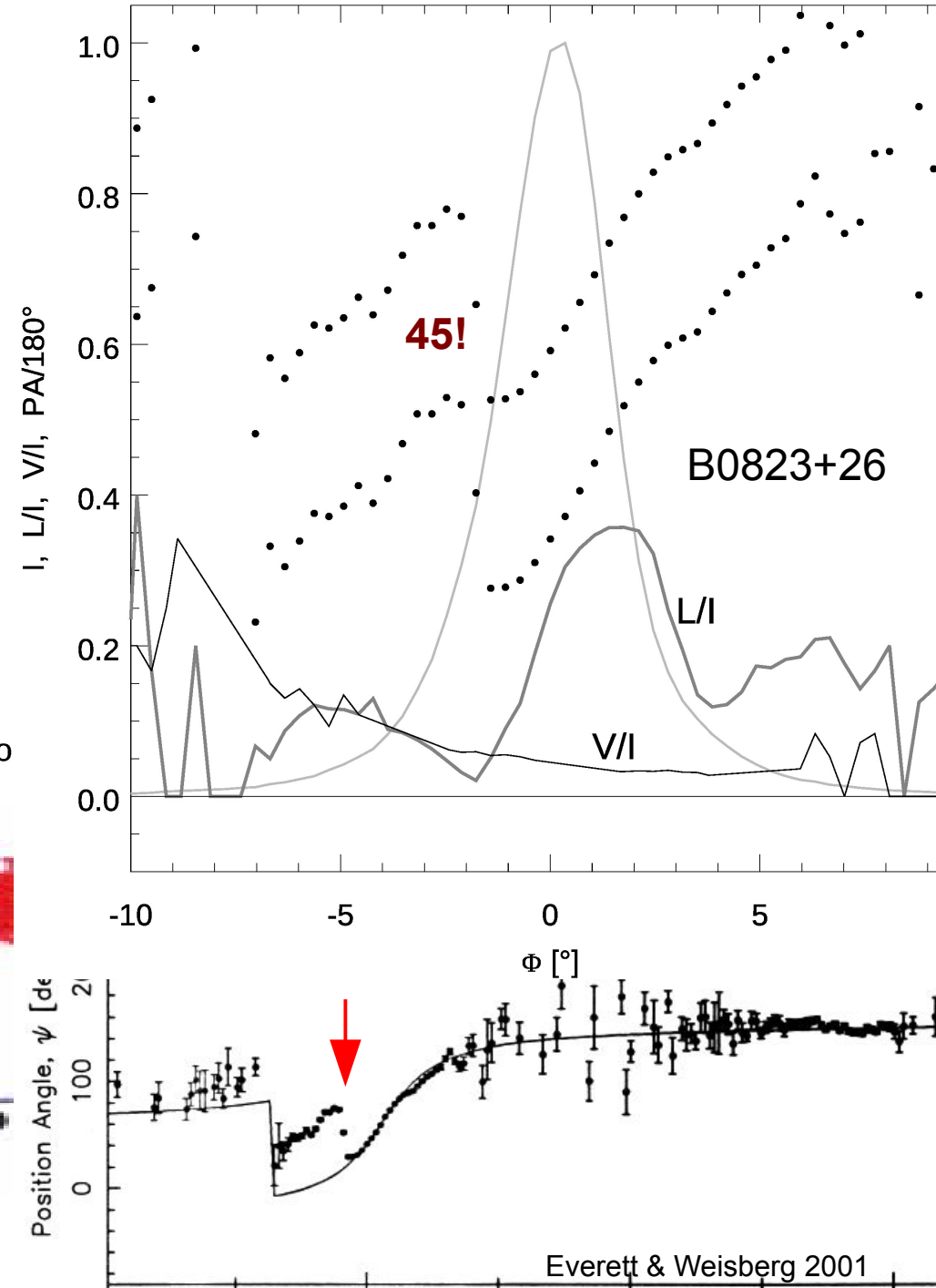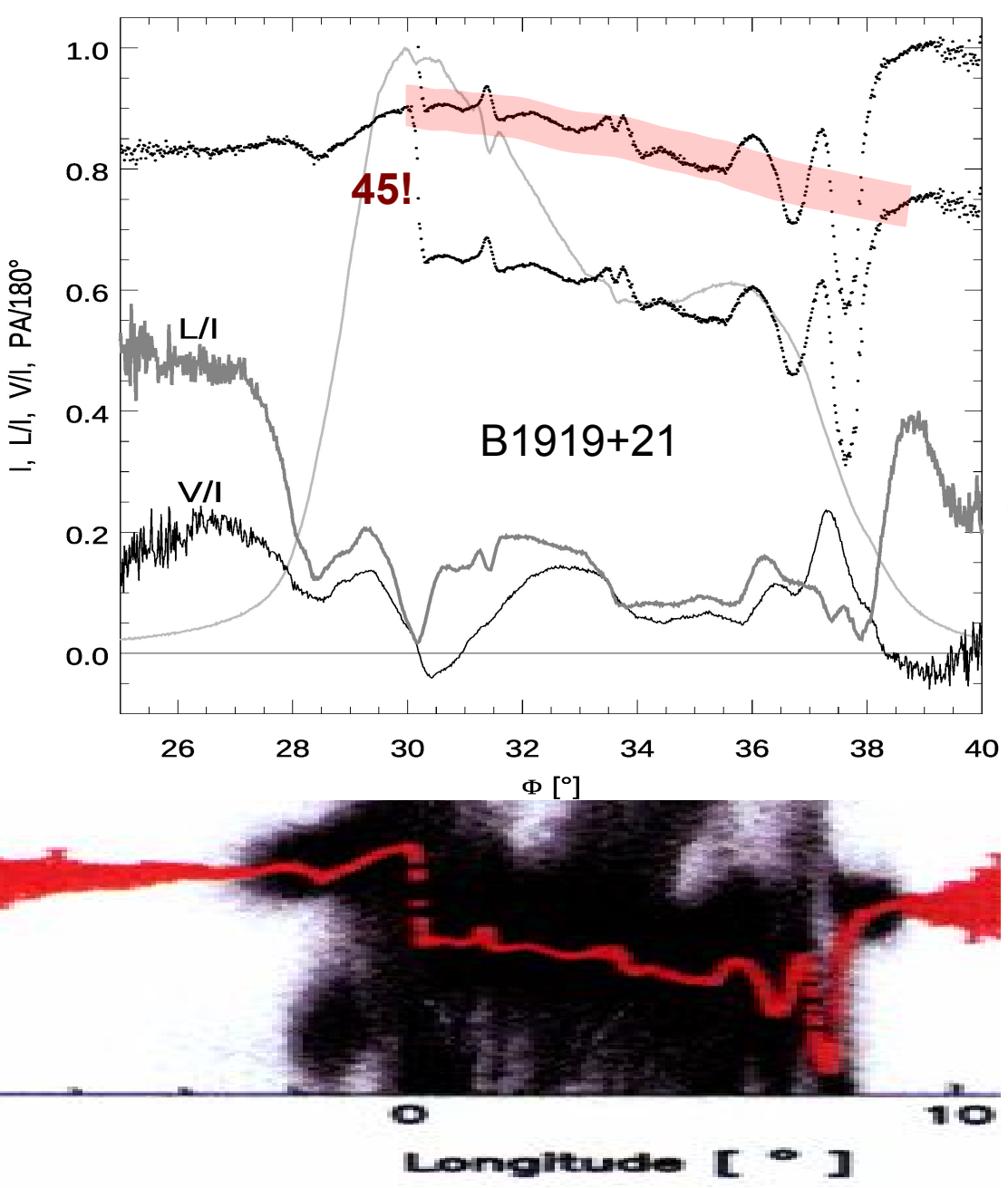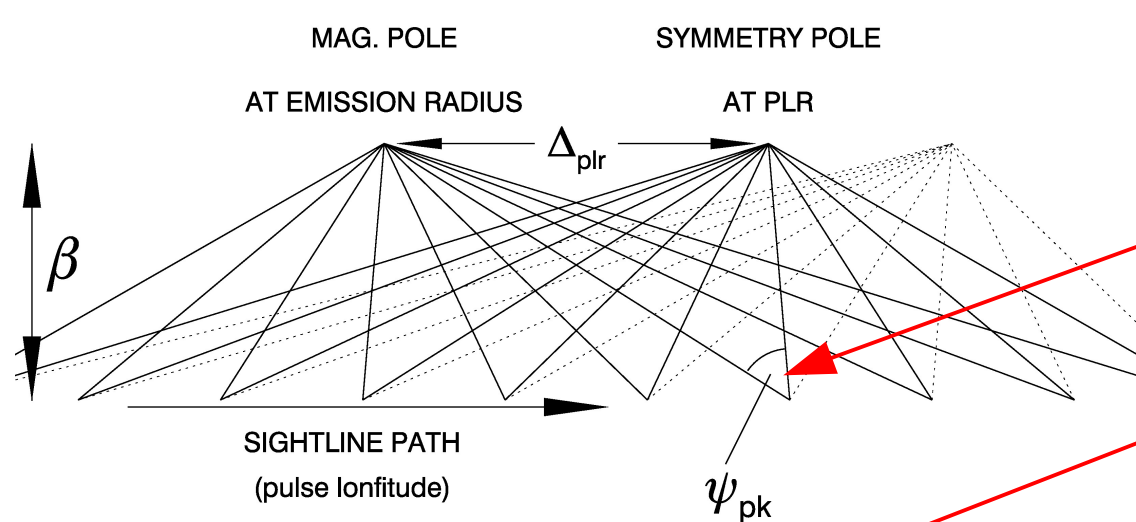
Mixing angle:

- estimated from the low-r/high-r electron trajectory misalignment

- strong changes in the core region of proflies (for small impact angle)

- hence the core PA distortions eg. in B1237

- high-r "B-field" (electron trajectories) provide the RVM shape

a) $\rho = 0.5\Delta_{plr}$

b) $\rho = \Delta_{plr}$

c) $\rho = 3\Delta_{plr}$

ψ_{pk} [deg]

pulse longitude [deg]

B1237+25
327 MHz

Total, Linear & Circular Power

Position Angle [°]

Longitude [°]

D17   SRM13
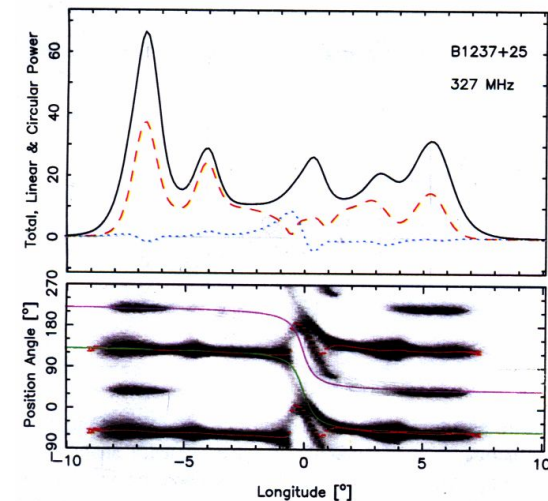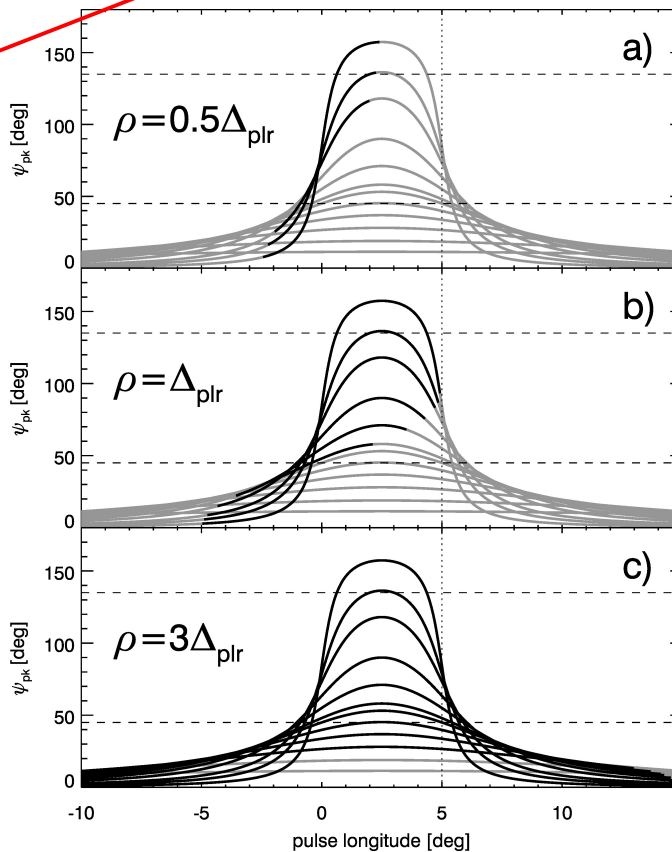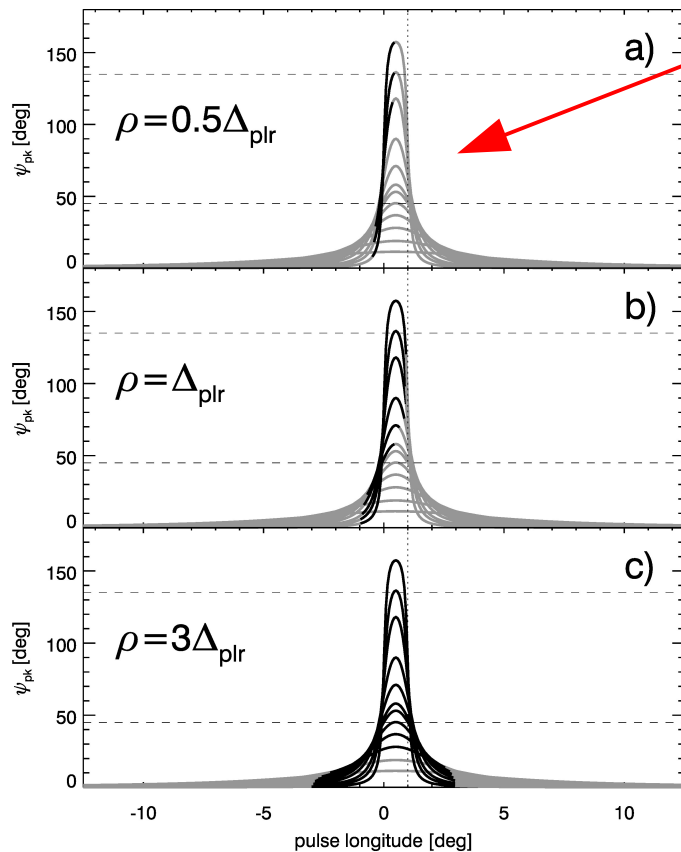
Conclusions

Coherent mode superposition crucial to understand complex pulsar polarization

Phase lag distribution important   (+ mode amplitude ratio)

Peculiar/complex polarization effects can be interpreted geometrically

(all polarization components at more than single nu)

**Complex core polarization from both lag-driven and amplitude-driven effects
overlapping in the same pulse longitude interval**

V from coherent superposition of linear modes

Nu-dependent polarization from phase lag change
(and mode ratio change)

=> intrinsically nu-dependent PA   => possibility of false RM
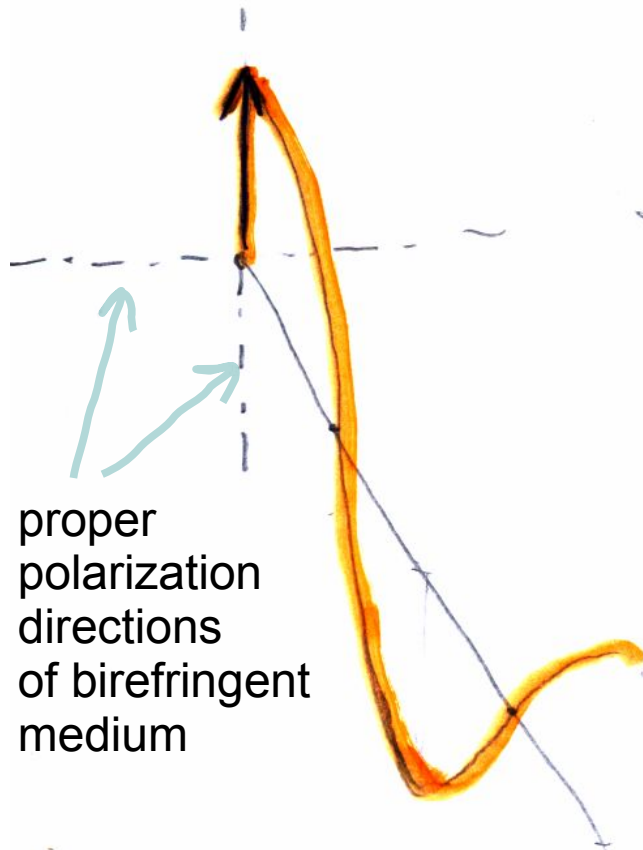
Several parameters, a lot of work to do

  - probing the parameter space,
  - average data fitting (J0437 at different nu),
  - single pulse data modelling
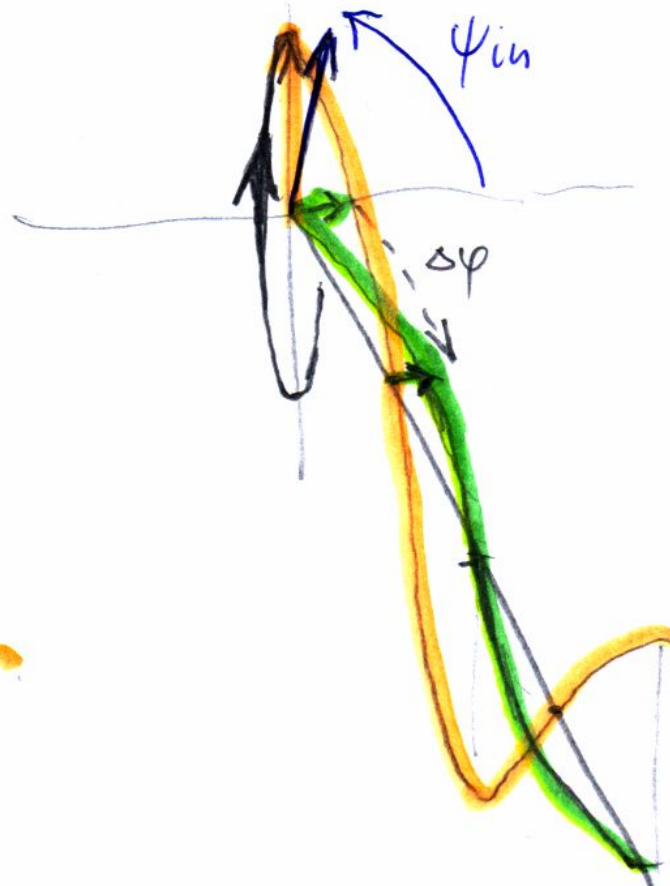
Phase lag = 90 deg

psi_in = MA = mixing angle

PA = polarization angle (for coherent sum)
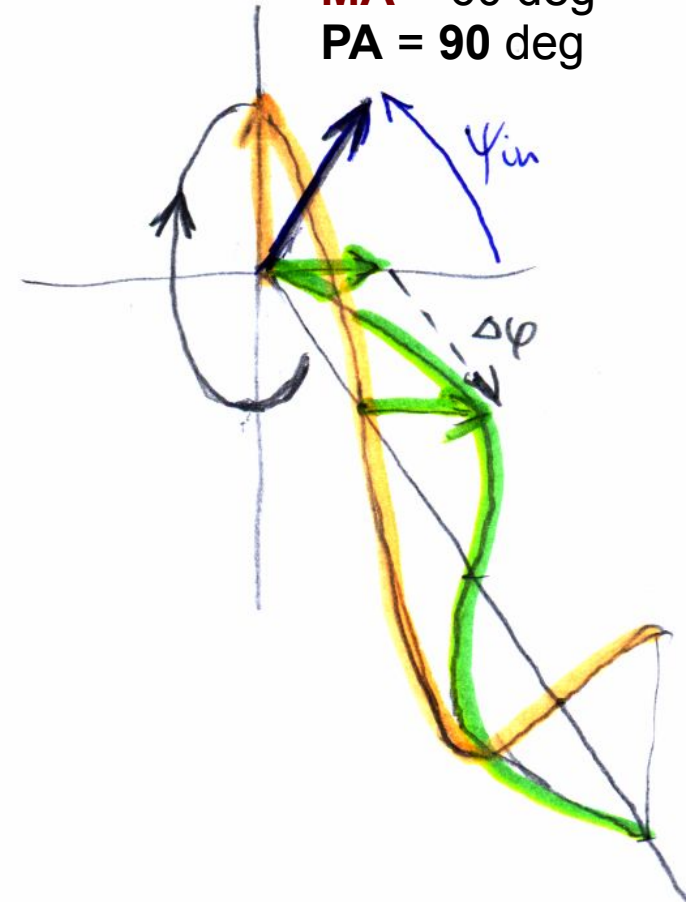determined by direction of ellipse major axis

MA = 90 deg
PA = 90 deg

MA = 80 deg
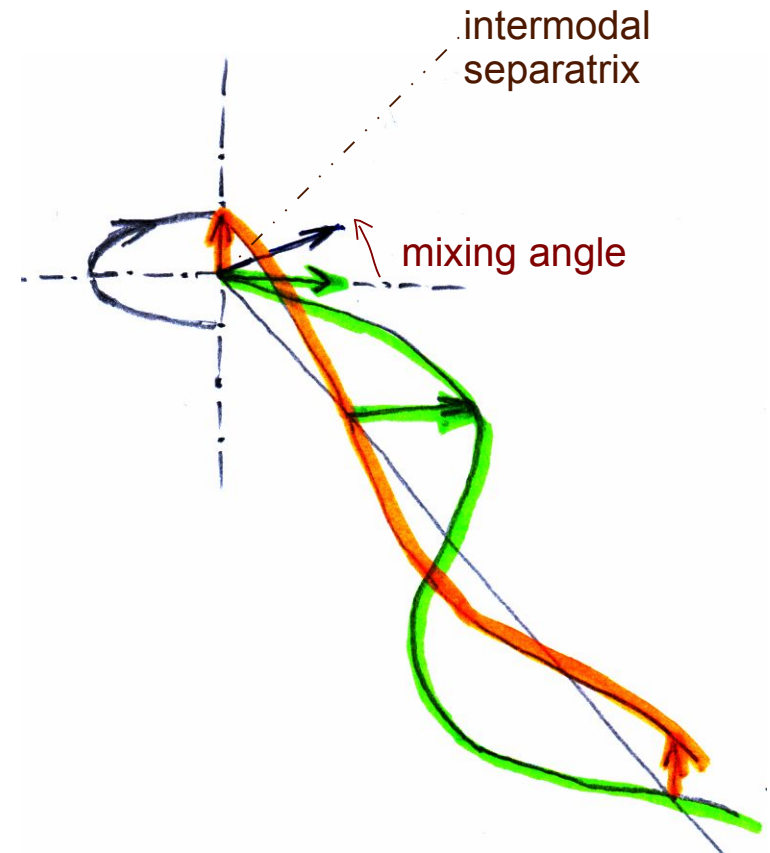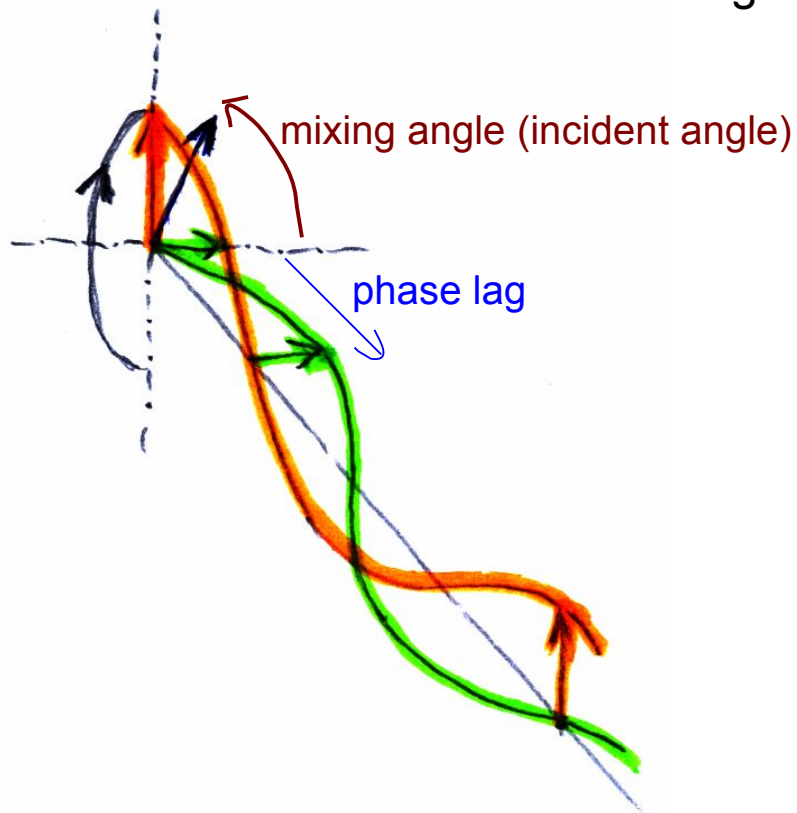PA = 90 deg

MA = 60 deg
PA = 90 deg

proper
polarization
directions
of birefringent
medium

The same PA for any mixing angle (for any mode amount ratio)

Coherent addition of phase-lagged modes

Orthogonal modes with the same sign of V

Phase lag = pi/2

We observe the coherent sum of modes, not just the modes.

The ellipses are the observed OPMs, not the orange and green waves separately.

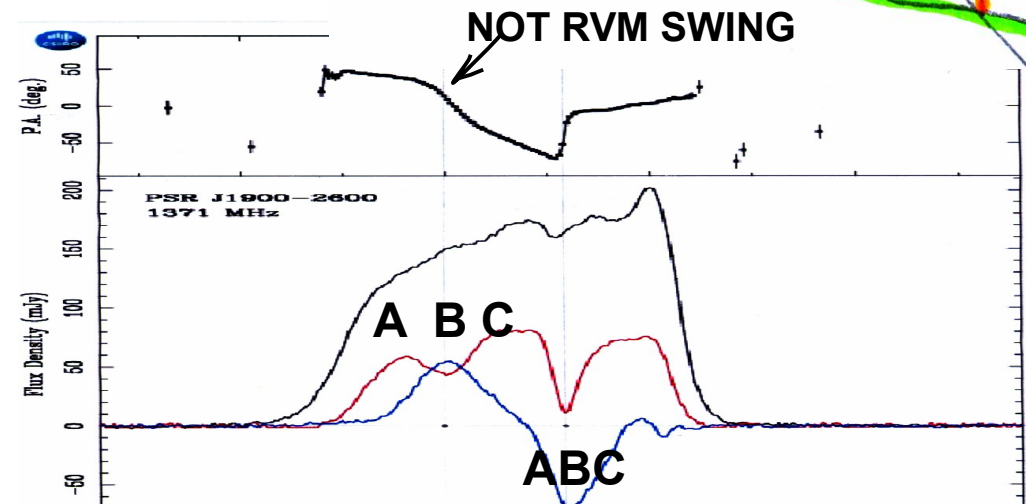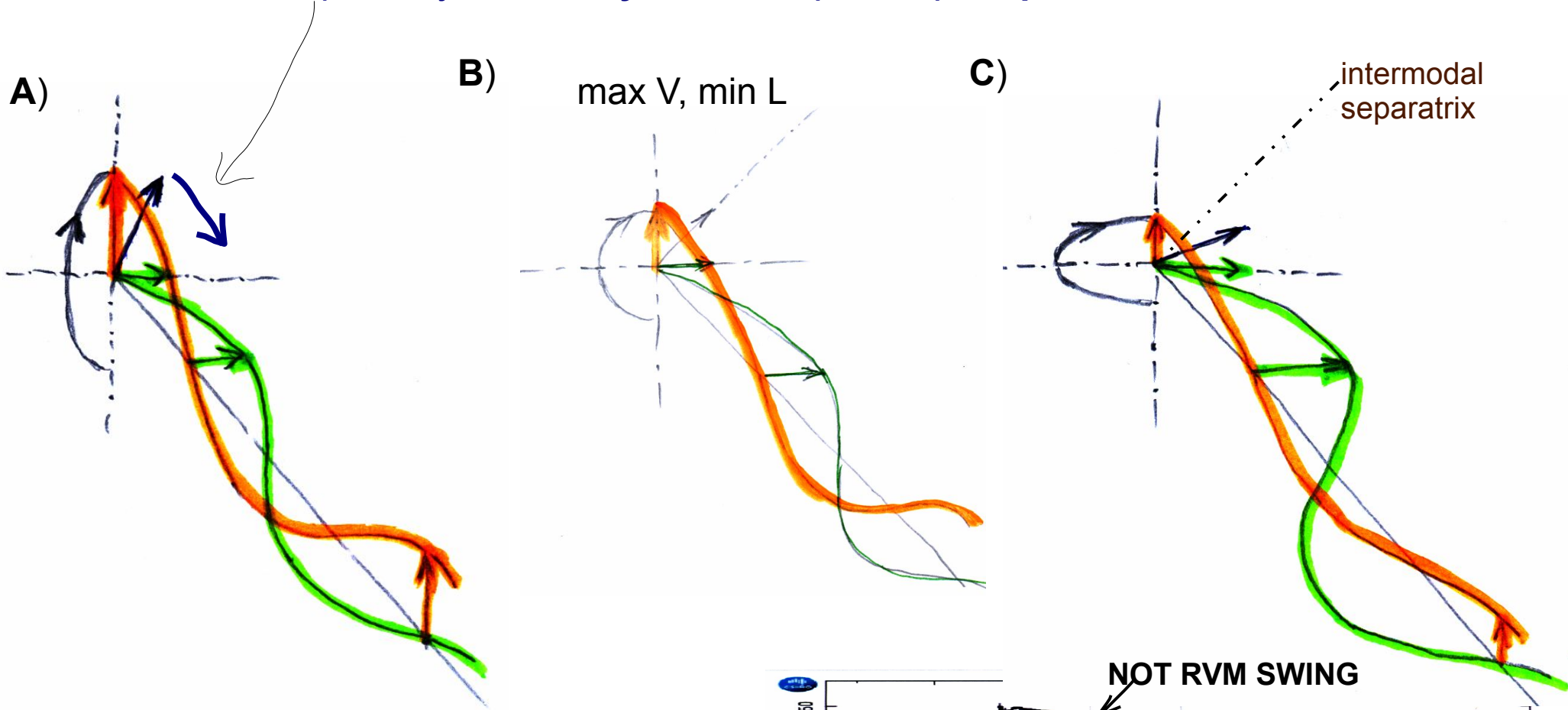Phase lag does not have to be equal to pi/2.
It is enough that the phase lag distribution extends up to pi/2.

Coherent OPM jump at maximum V

phase lag ~ pi/2

mixing angle slowly decreasing with longitude
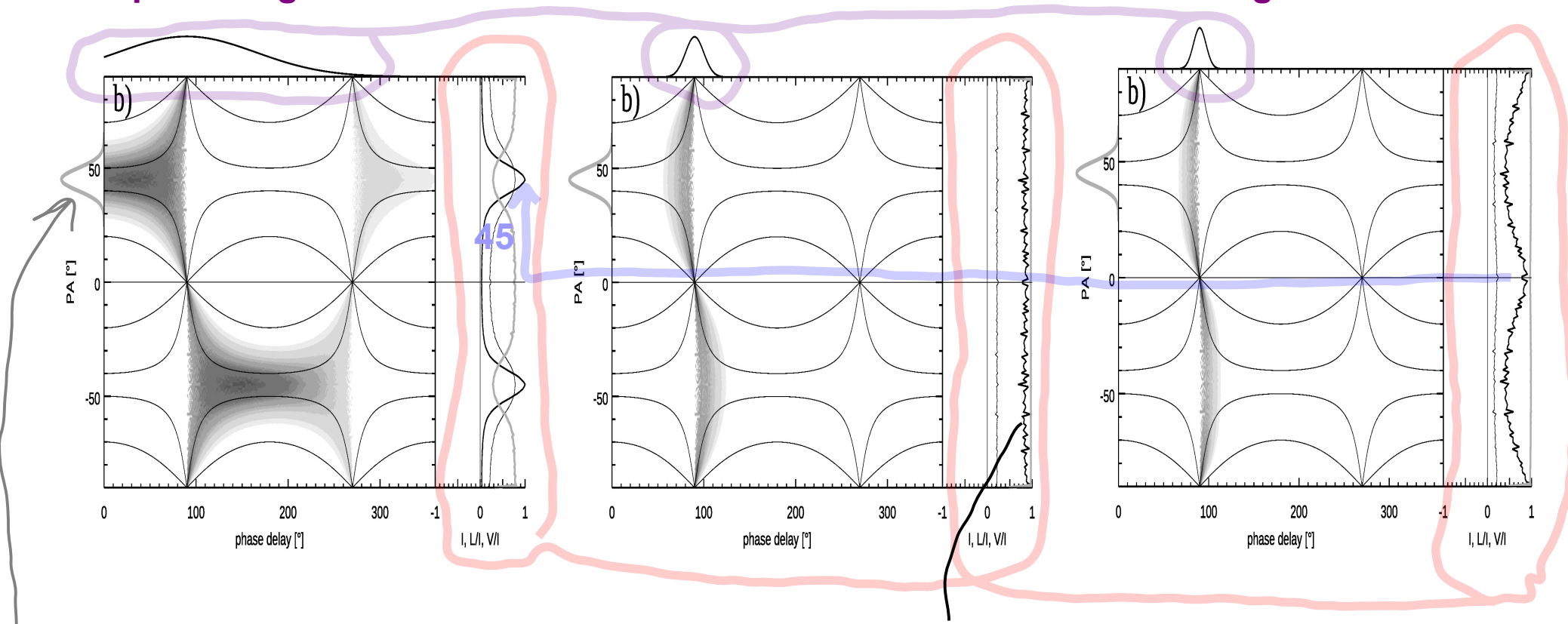Ellipse major axis **stays vertical (flat PA) despite** the vector rotation

A)

B) max V, min L

C) intermodal separatrix

NOT RVM SWING

PSR J1900-2600
1371 MHz

P.A. (deg.)

Flux Density (mJy)

A B C

ABC

Narrowing of phase lag distribution
Equal mode amplitudes

= transition from incoherent to coherent mode mixture

Wide phase lag distr.
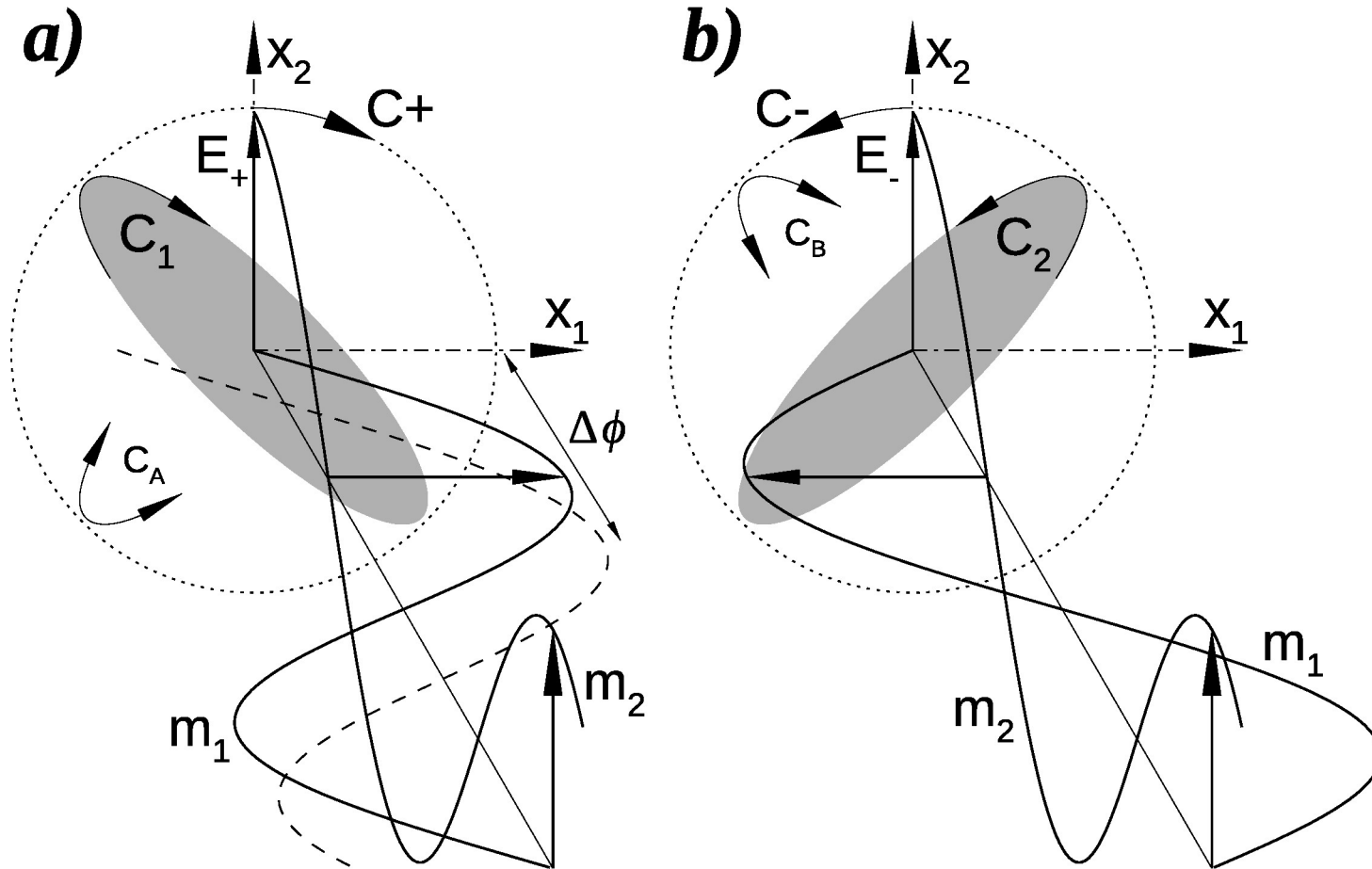
Narrow lag distr.
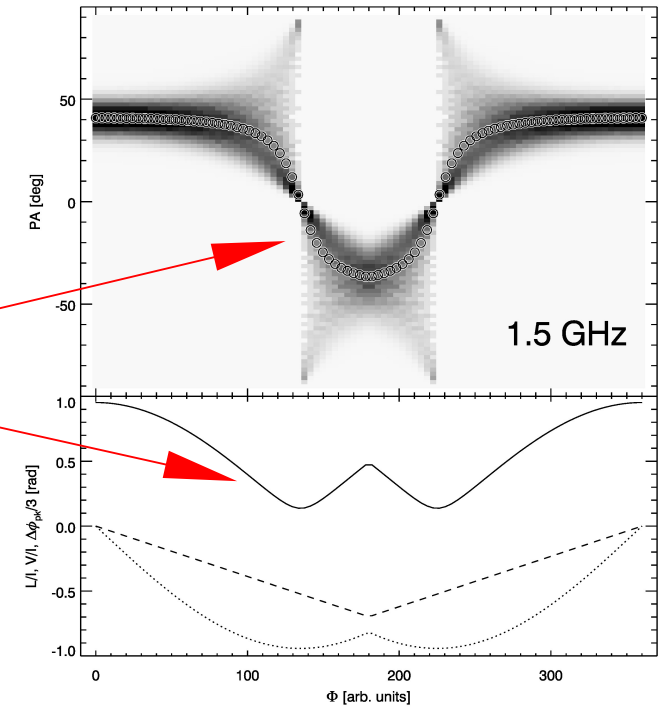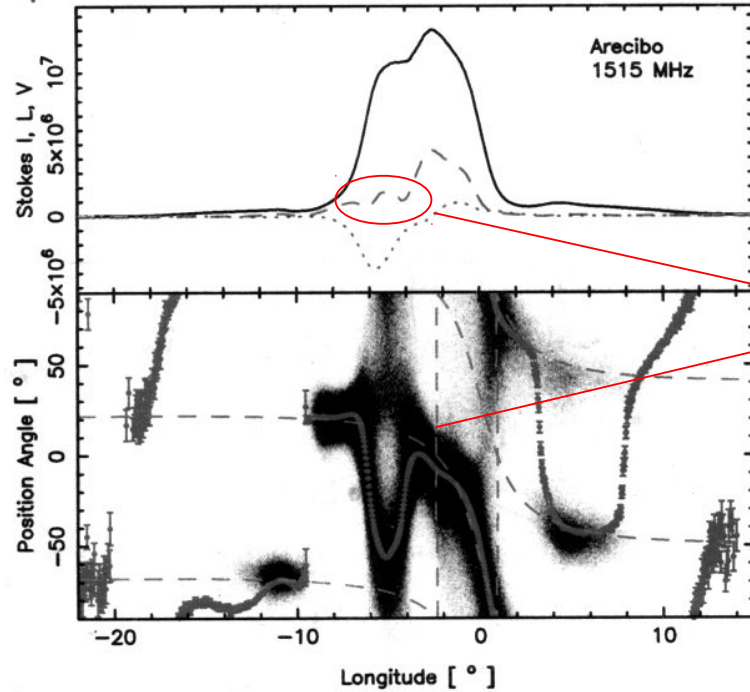

thick solid: PA distr. at fixed longitude

Equal mode amplitudes => mixing angle = 45 deg

Preference for equal amount of modes

Circularly-polarized wave entering linearly birefringent medium

D2019

Multiple interpretations possible: longitude-dependent lag
mix. ang. = f(nu)

Arecibo
1515 MHz

1.5 GHz

Model works
at both nu

Features
reproduced:

- PA loop/U-distort.
- twin minima in L/I
- large V/I

Arecibo
4555 MHz

4.5 GHz

Mitra et al. 2016

Dyks 2017